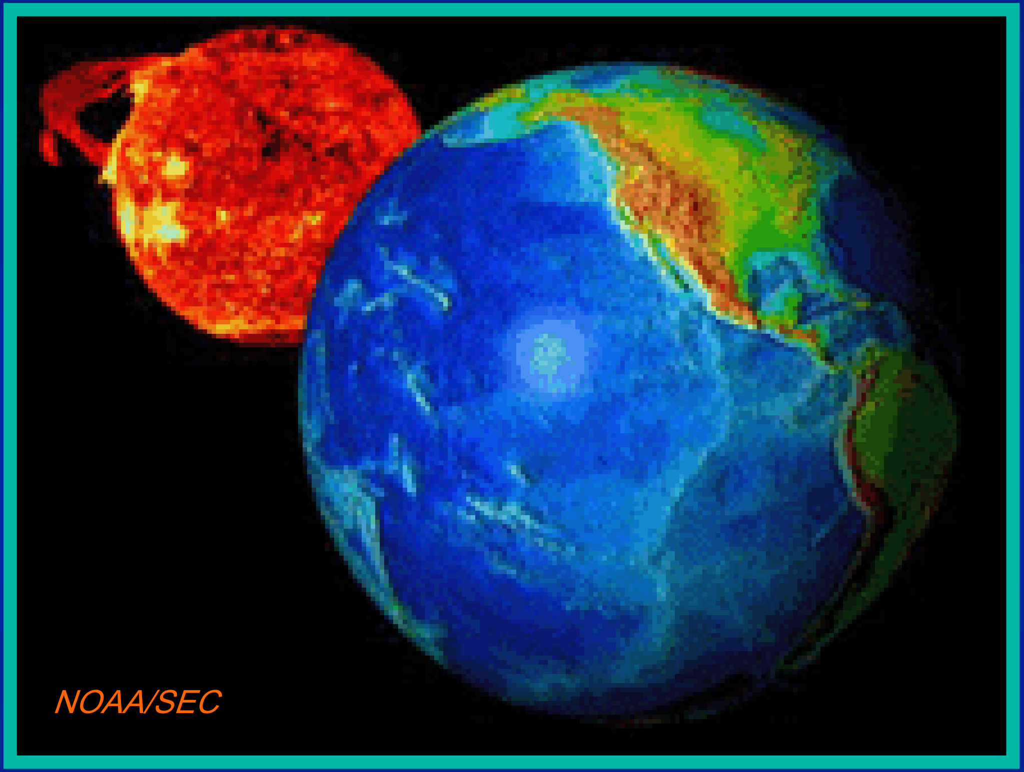
Space & Atmospheric Environments



Janet L. Barth

NASA/Goddard Space Flight Center

Flight Electronics Branch/Code 561

Acknowledgements

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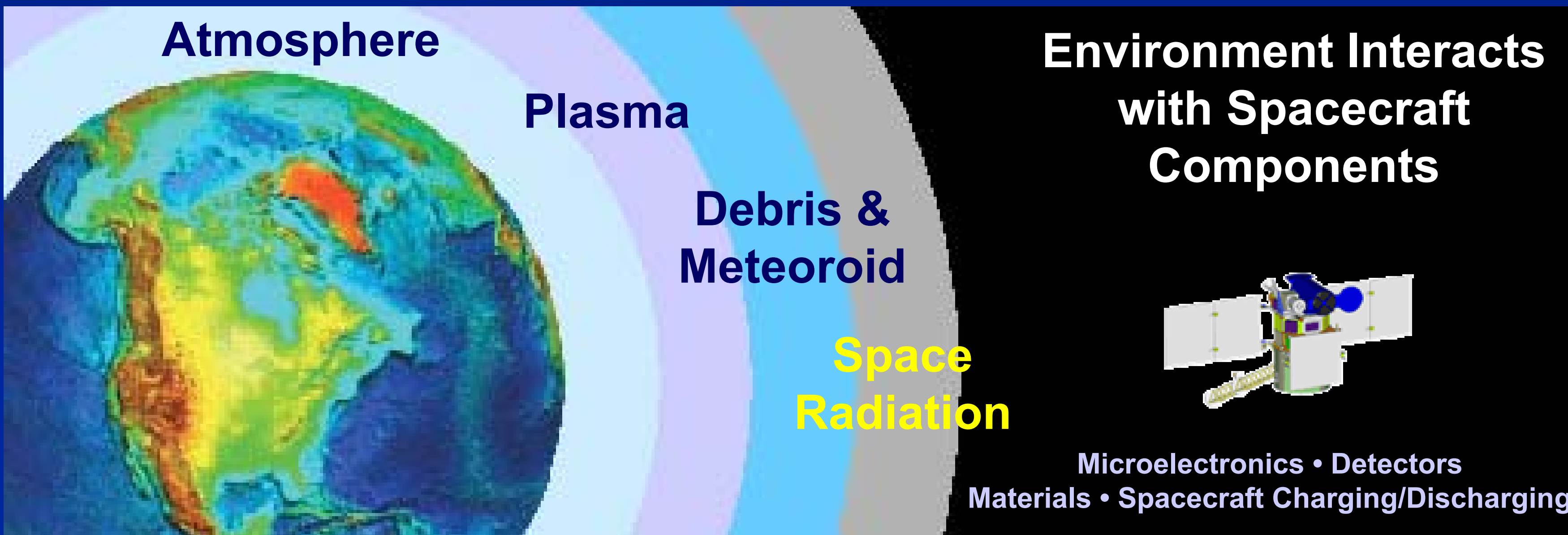
  - Head, Radiation Physics Office (RPO)
- Ken LaBel
  - Group Leader, Radiation Effects and Analysis (REA)
- Members of RPO and REA
  - CS and contractors

Outline

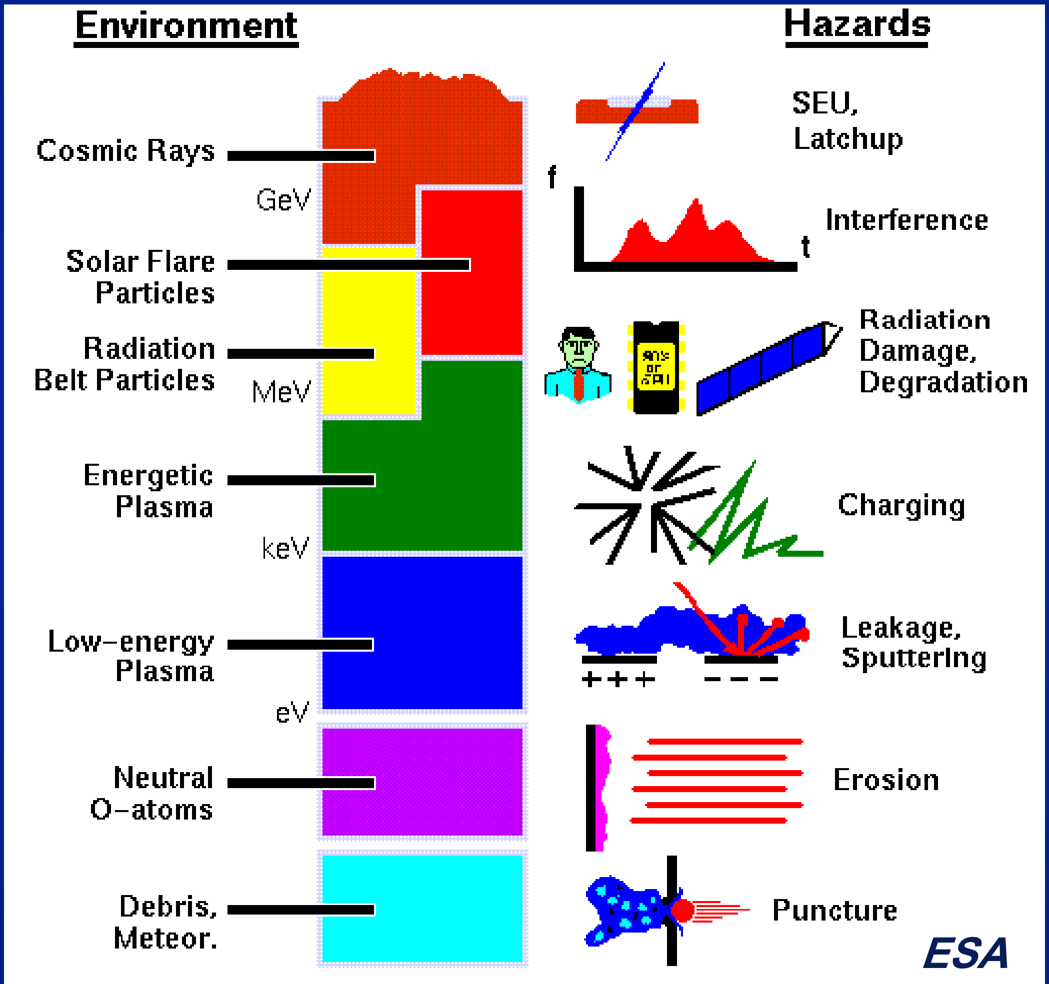
- Solar Processes
- Space Climate/Space Weather
- Radiation Environments Description
- Radiation Effects
- Radiation Environment Specification
- Summary for Radiation Environments
- Atmospheric Environments

Natural Space Environments



- Design and operation of reliable systems in space environments require systems engineering approach
- Ref: "Emerging Radiation Hardness Assurance Issues: A NASA Approach for Space Flight Programs", LaBel et al.

Environmental Hazards

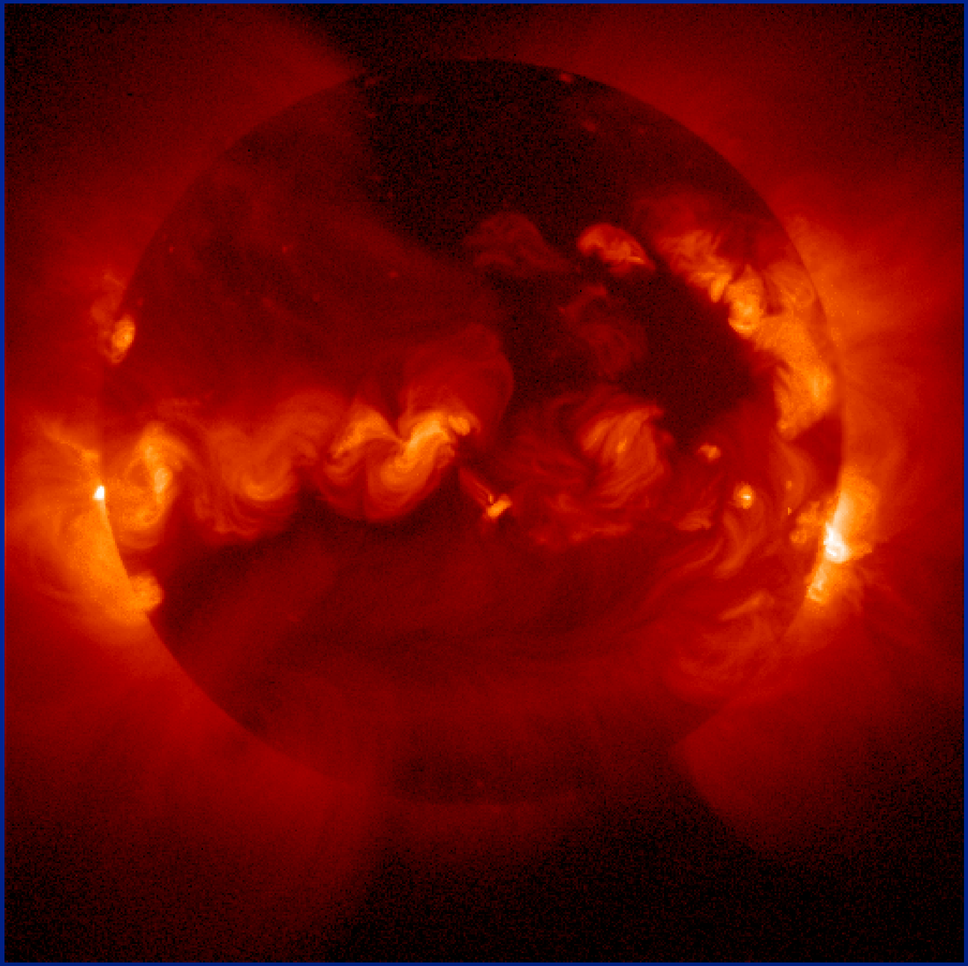


- Low Earth Orbits (LEO)
  - » Low Inclination
  - » Polar
- Middle Earth Orbits (MEO)
- Geostationary (GEO)
- Interplanetary – AU dependent
- Jovian

Solar Processes

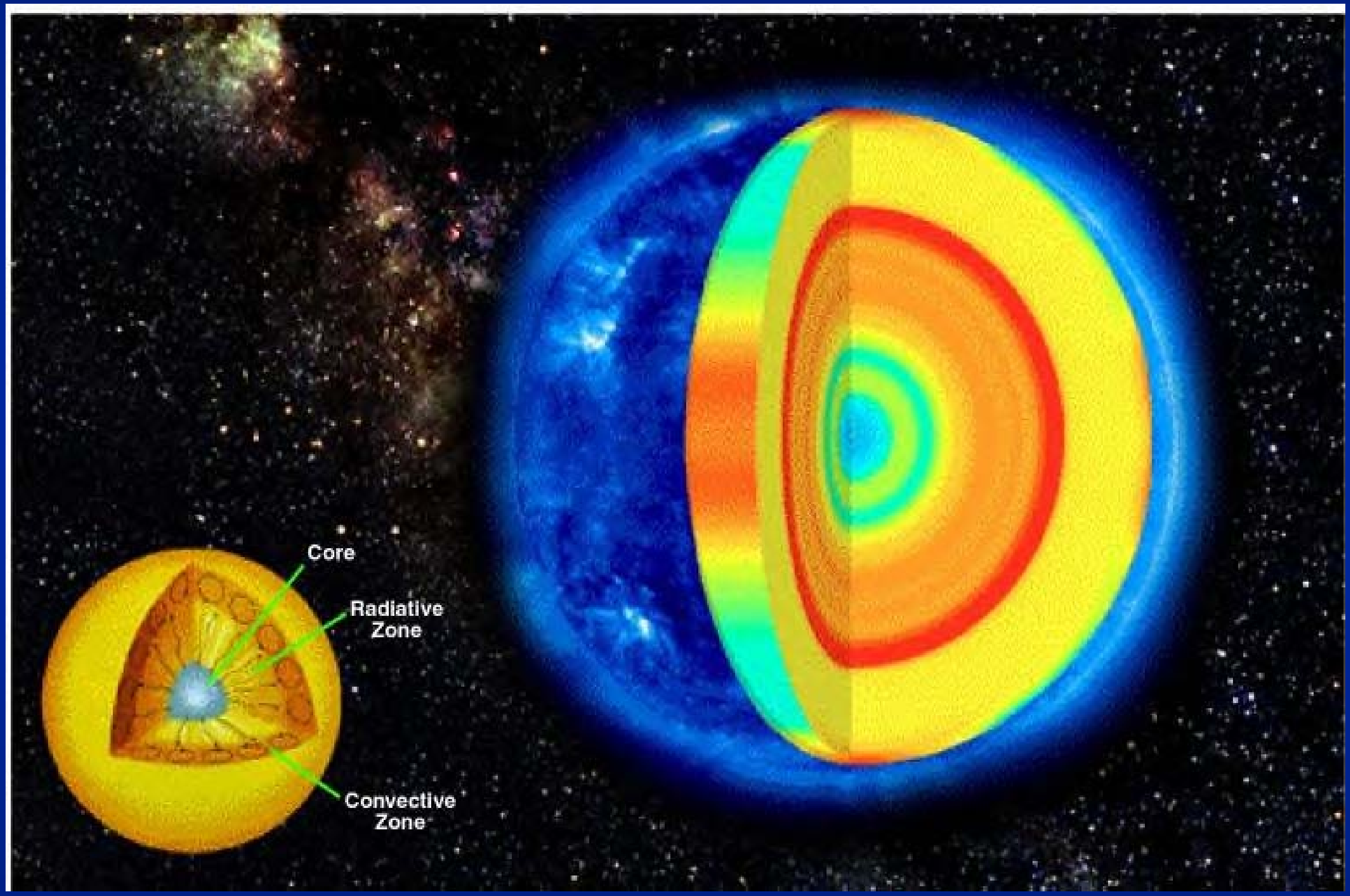
The Sun

- Dominates space environments
  - Source
  - Modulator
- Strongly affects atmospheric environments
- Structure
  - Photosphere
  - Chromosphere
  - Corona



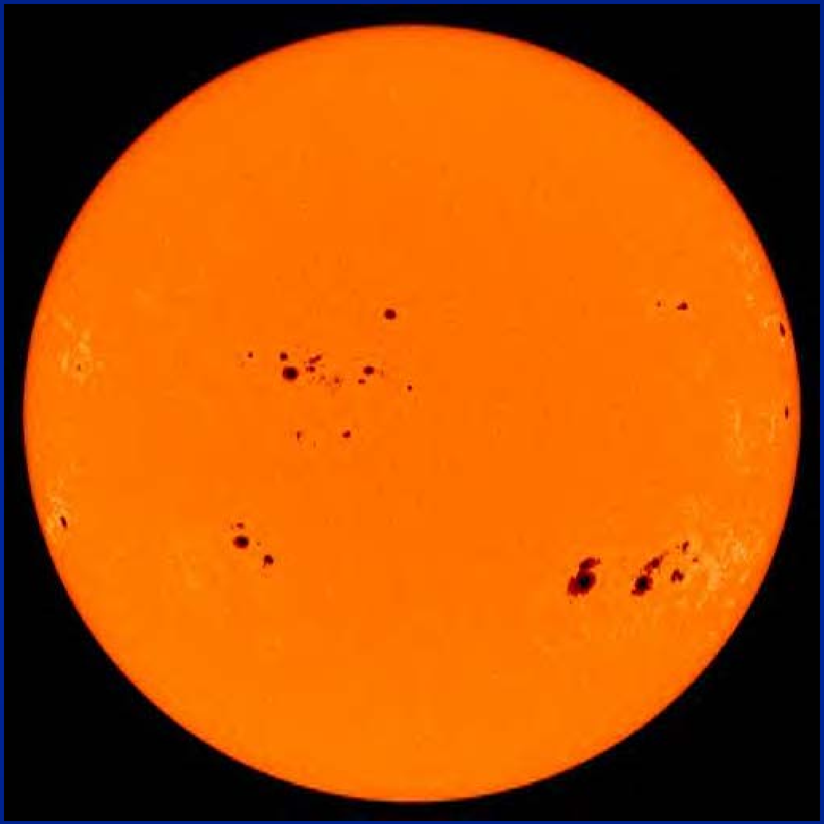
Yohkoh/SXT

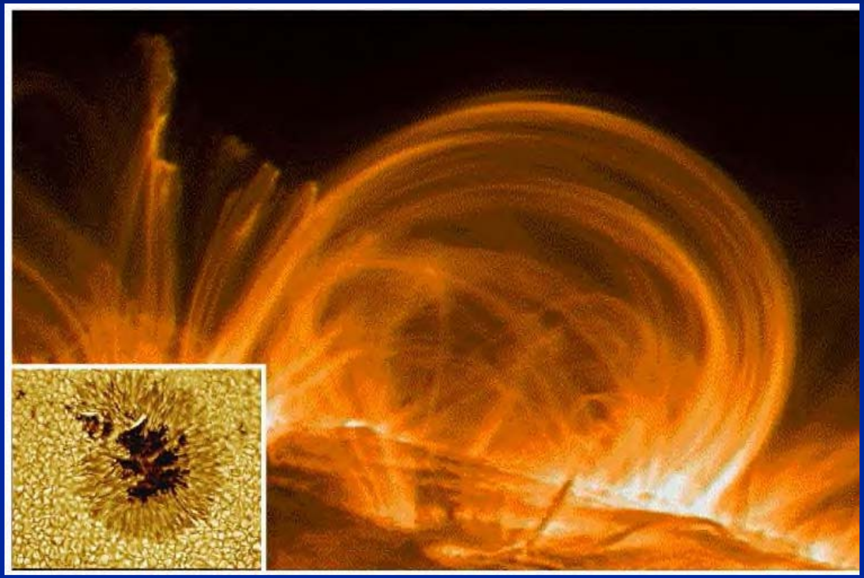
The Solar Interior



The origin of all the energy from the sun is deep inside its core where 600 million tons of matter turn into energy every second.

Sunspots



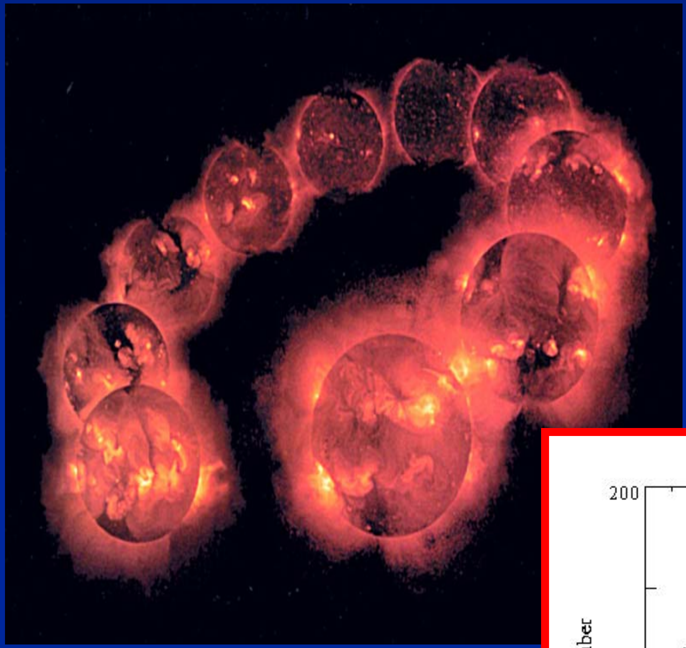


Discovered by Galileo in 1610

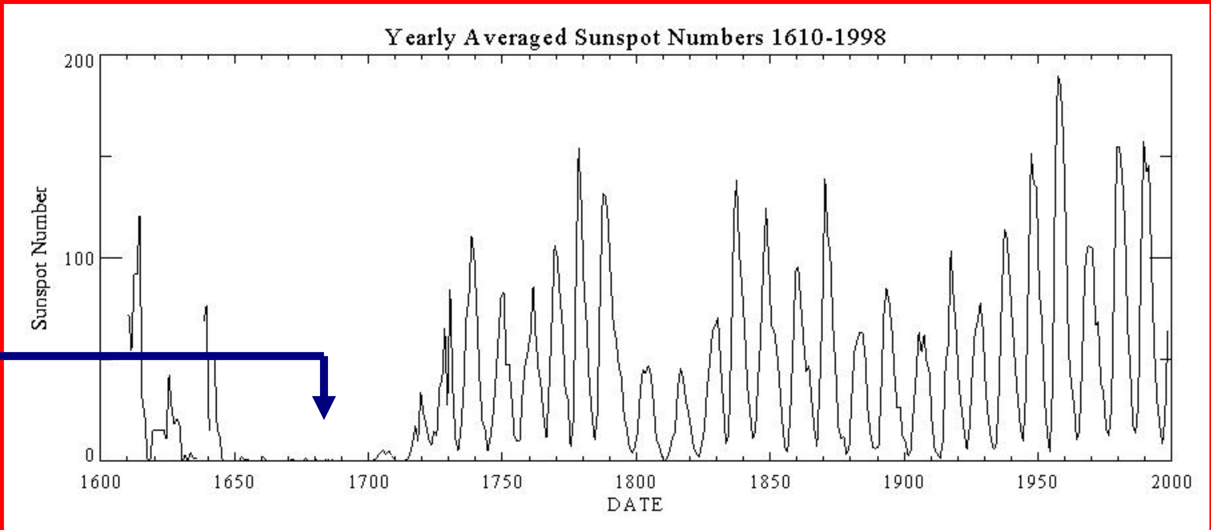
Sunspots are the most obvious indicators of an unsettled Sun.

They are regions of transient, concentrated magnetic field and are cooler than their surroundings.

The 11-Year Solar Activity Cycle



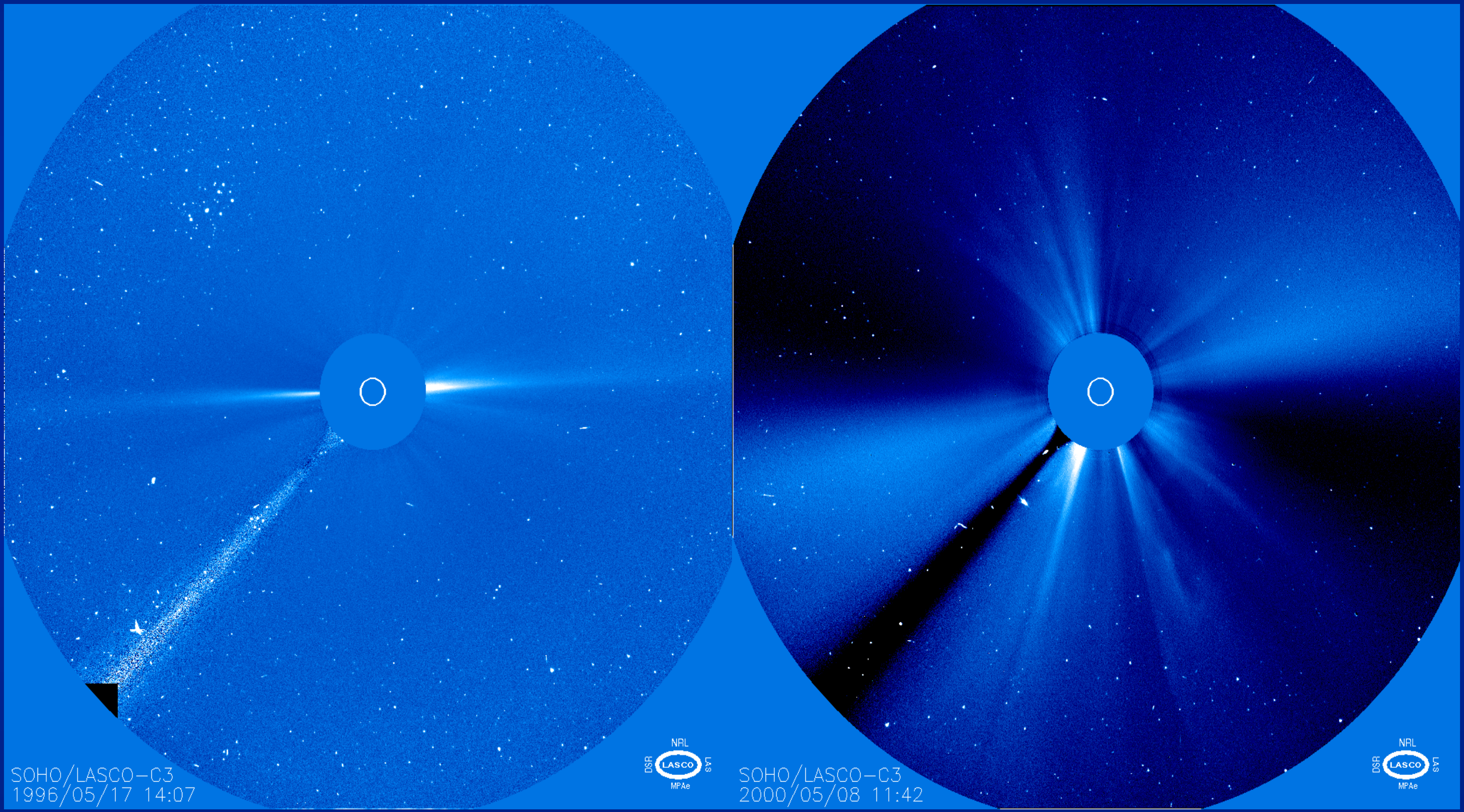
Sunspot cycle discovered by Schwab in 1844



Little Ice Age in 1645 to 1715

Length varies from 9 - 13 years
7 Years Solar Maximum, 4 Years Solar Minimum

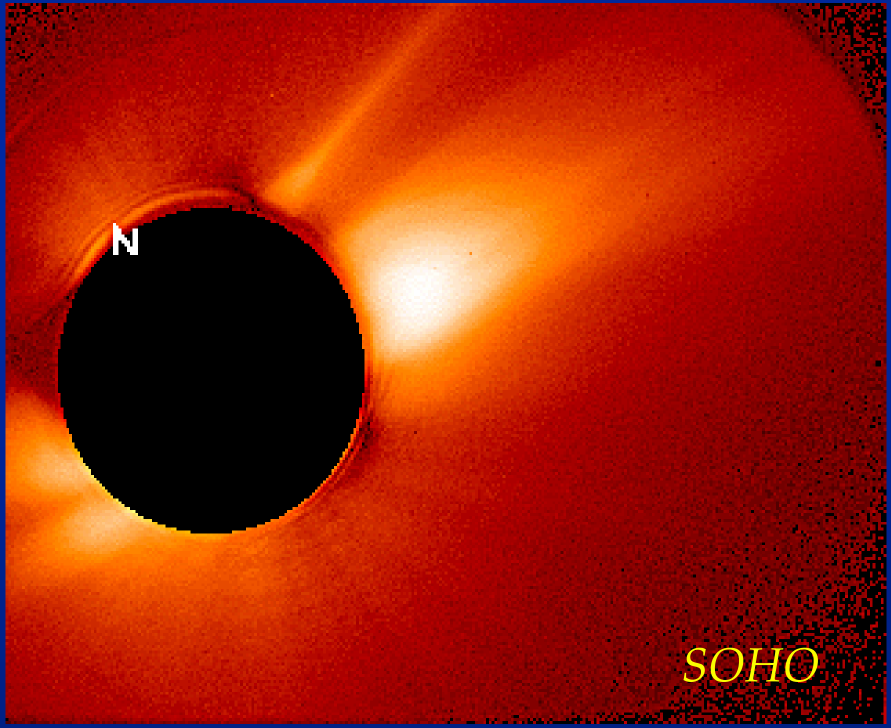
Solar Minimum - Solar Maximum



SOHO/LASCO

Corona

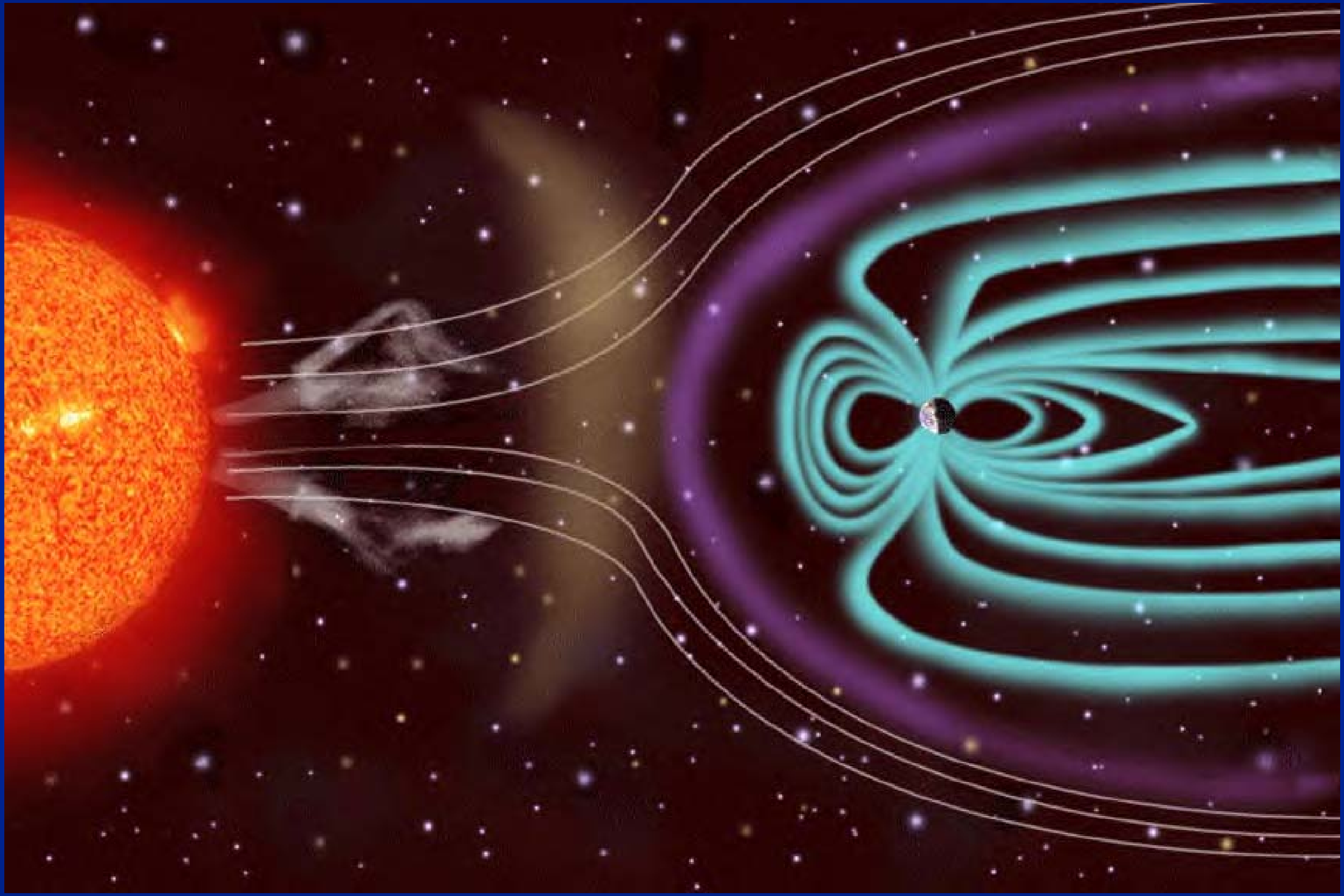
- Solar wind source
- Highly structured region of plasma
- Expands outward, parallel to solar field lines



Solar Wind

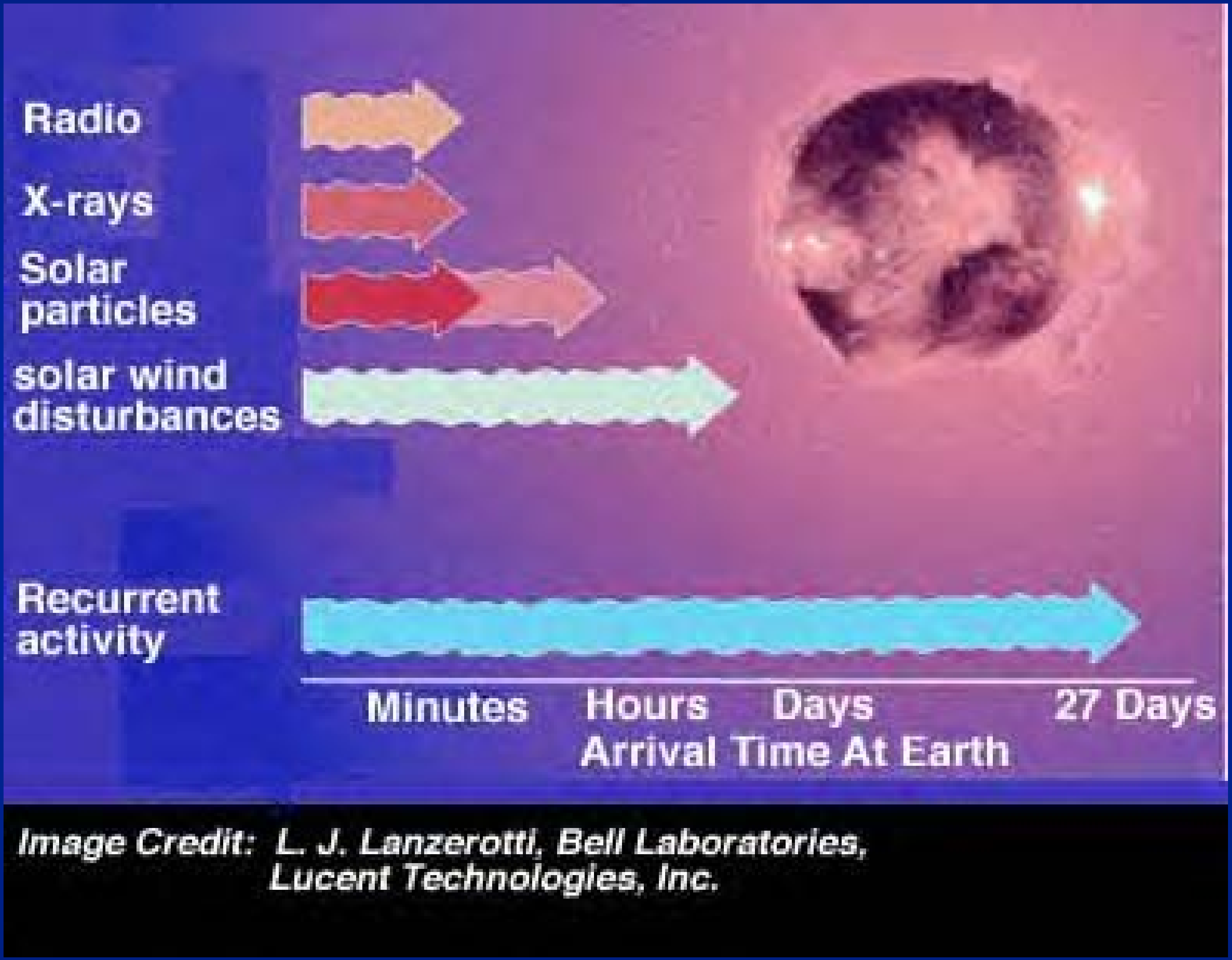
- Stream of charged particles
  - Electrons
  - Protons
  - Heavy ions
- Detected out to 10 billion km from Earth by Pioneer 10
- Velocity ~ 300 - 900 km/s
- Energy ~ .5 - 2.0 keV/nuc

Solar Wind

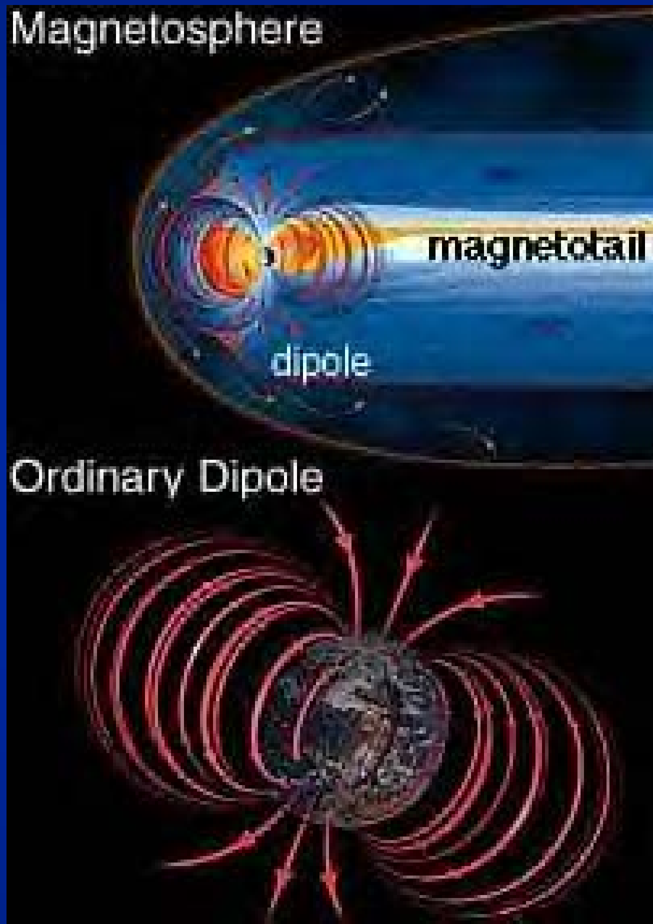


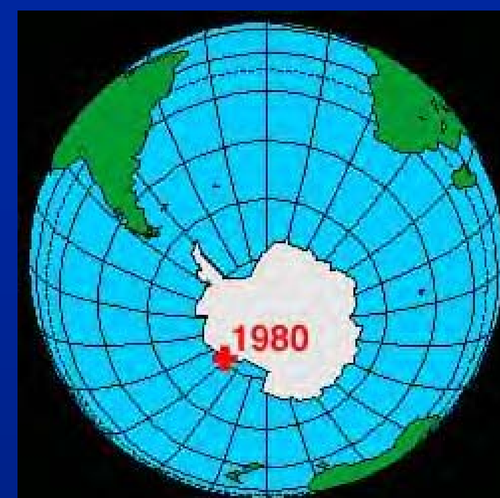
Solar wind transports energy from the sun to interplanetary space.

Solar Energy Transmission to Earth



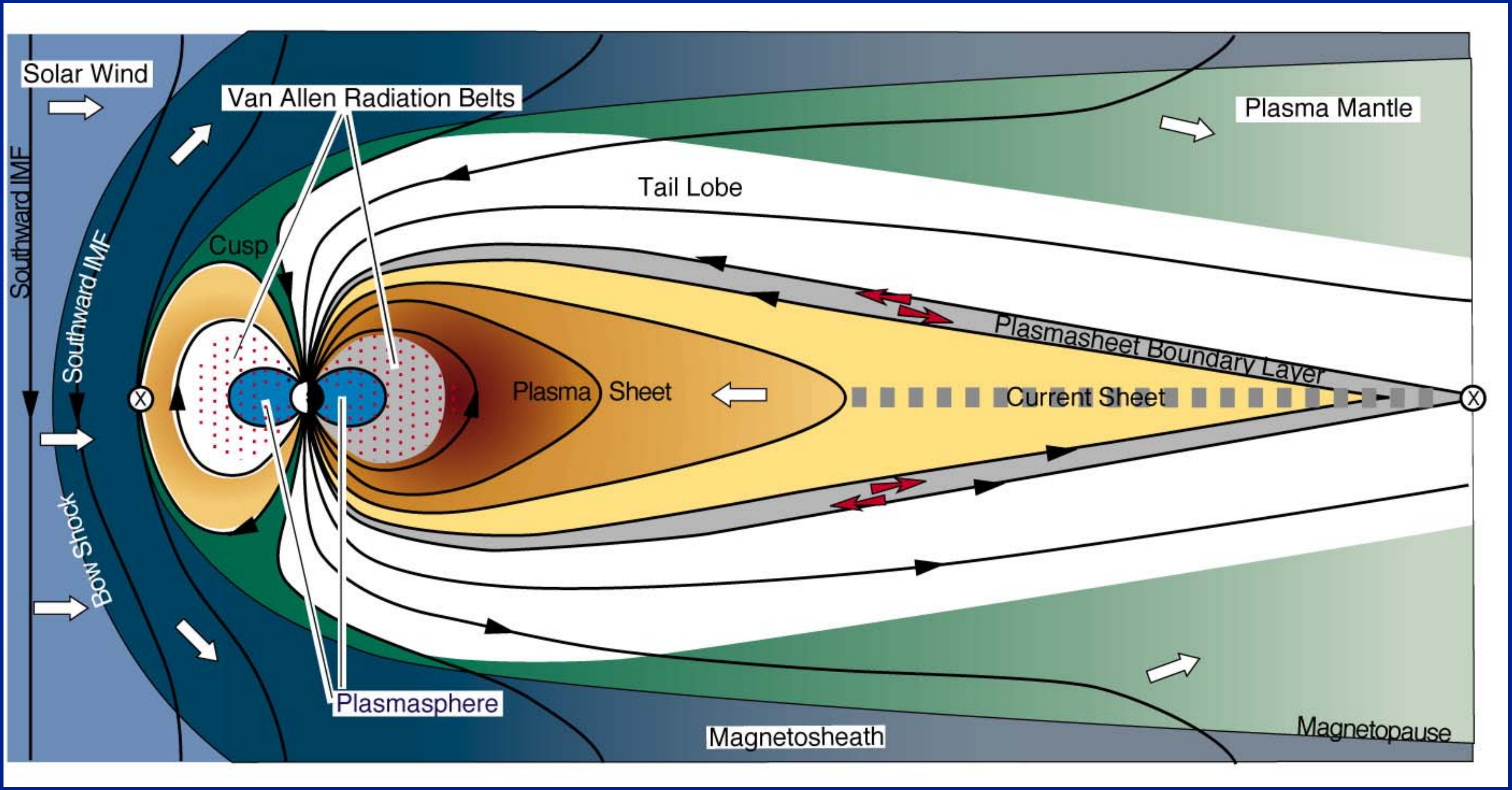
Magnetosphere





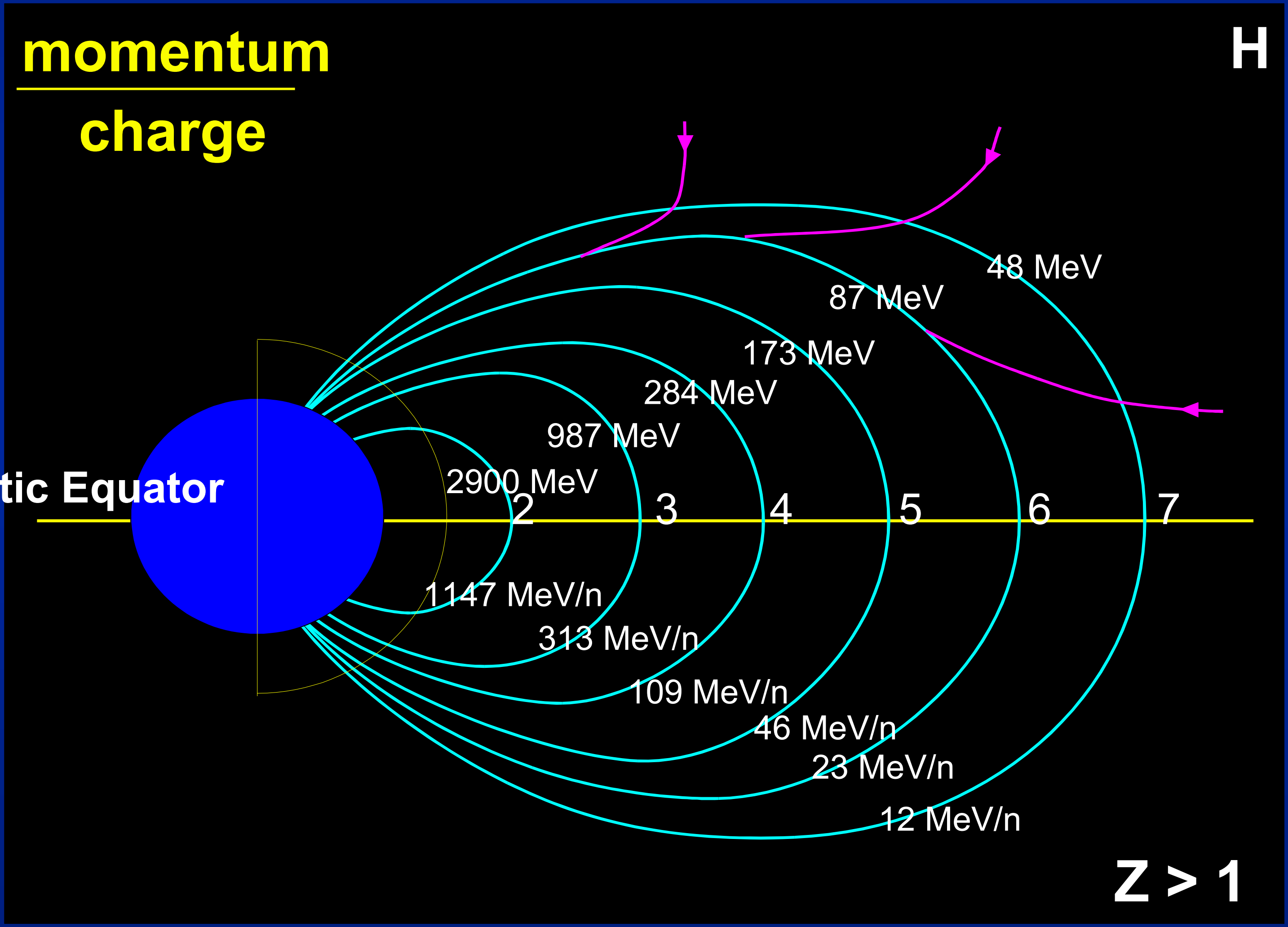
An invisible cloak of magnetism protects the Earth from much of the Sun's storminess.

Magnetosphere



Magnetic Rigidity

Total Energy Required to Penetrate the Magnetosphere



after Stassinopoulos

Space Climate – "what you expect"
Space Weather – "what you get"

What is Space Weather?

- Definition
  - *"conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life of health"*

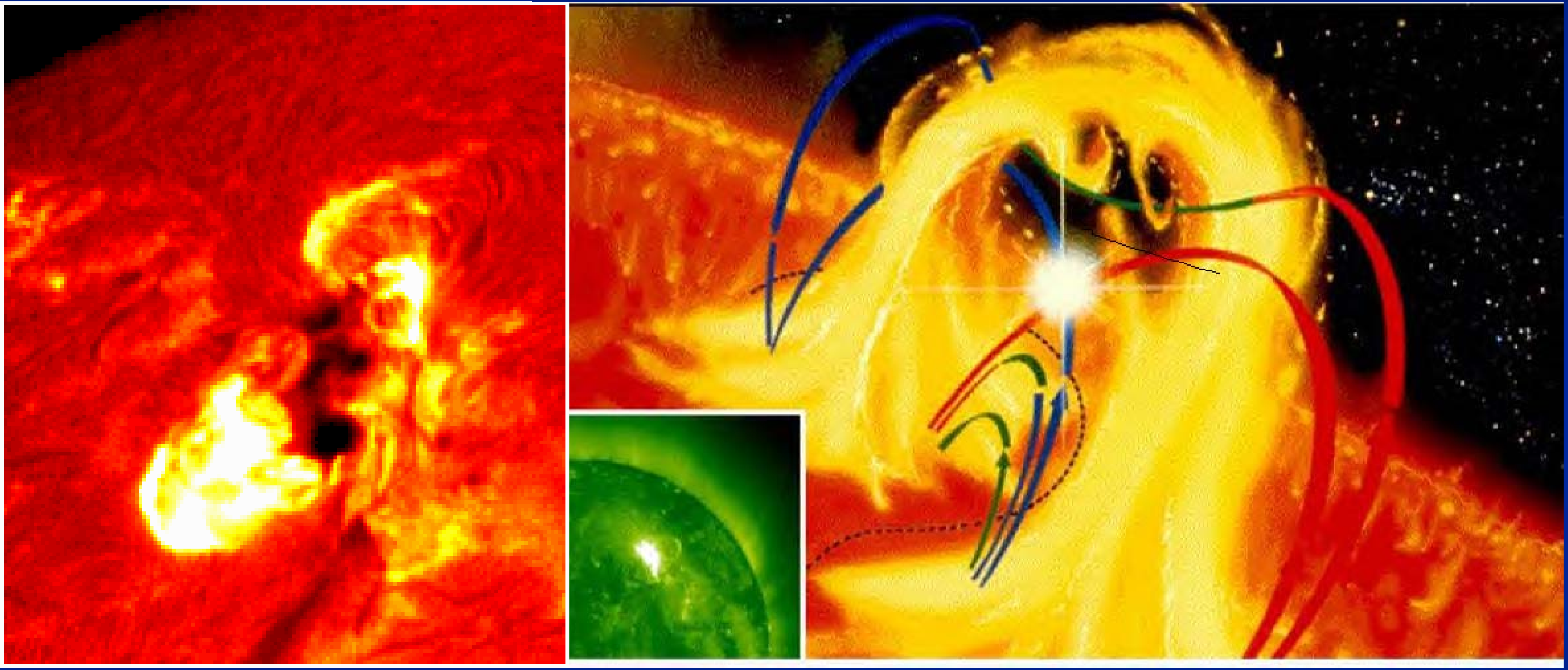
    [US National Space Weather Program]

- Space weather is a complex series of events
  - Begins deep inside the Sun and extends throughout the solar system, carried by the solar wind
  - Most of this weather is both invisible and benign, but occasional severe storms can shake the Earth's magnetic field.
  - Results in aurora, electrical power blackouts, communication problems, and satellite outages.

Effects of Space Weather

- Environmental effects
  - Storms and substorms in the Earth's magnetosphere
  - Increased proton & heavy ion particle counts
  - "Pump up" the Van Allen Belts
  - Ionospheric disturbances
  - Increased levels of atmospheric neutrons
- Consequences
  - Increased atmospheric drag on Low Earth Orbit (LEO) satellites
  - Increased radiation exposure on astronauts
  - Spacecraft reliability problems – radiation damage, false signals on circuits, electrical discharges
  - Power black-outs on Earth
  - Interference in some radio communication
  - Interference with cellular phone systems
  - Interference with GPS navigation
  - Increased radiation exposure on aircraft

Solar Flares

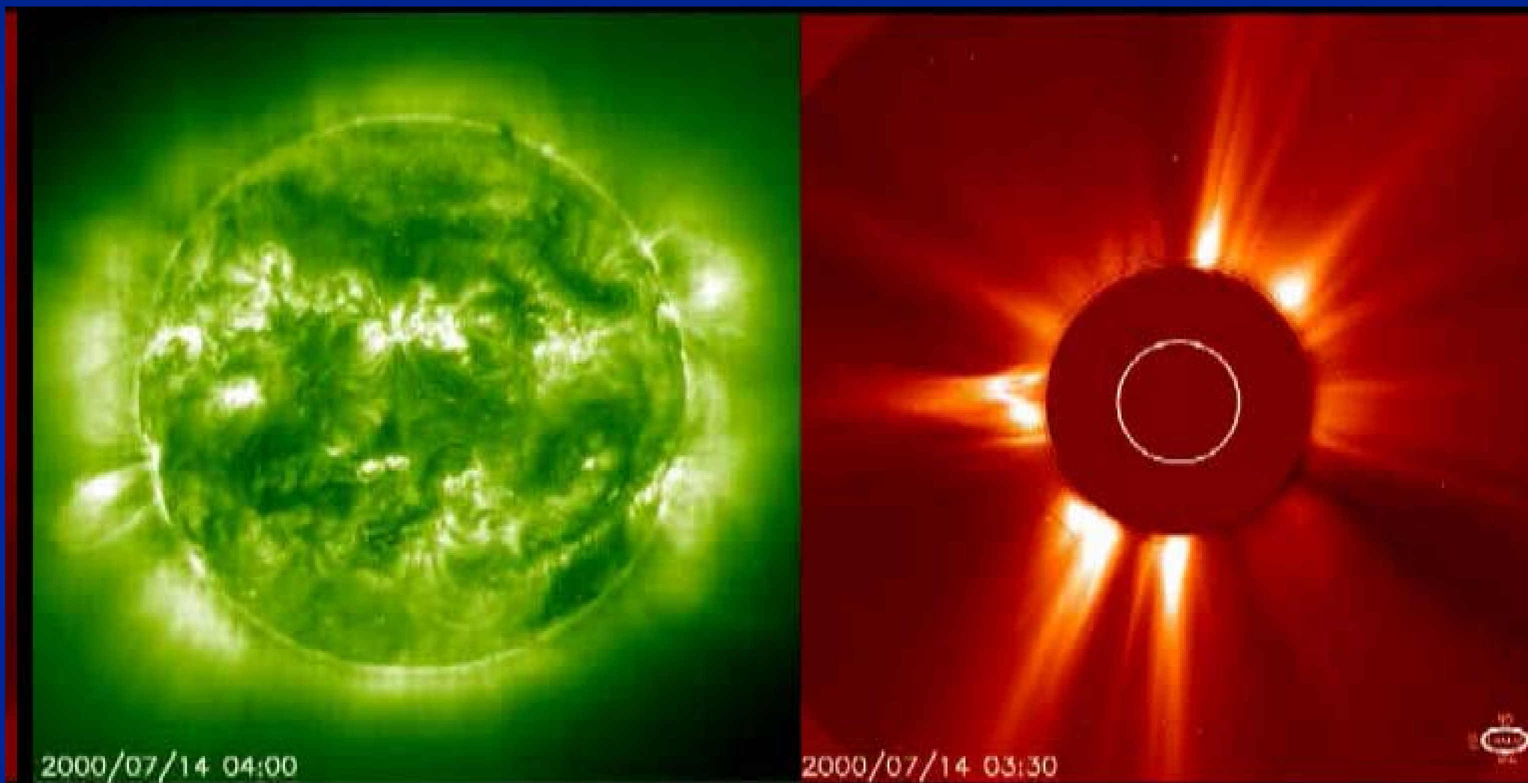


Solar system's largest explosive events during which particles are accelerated directly by event

Heavy ion rich solar events may be due solar flares.

Solar Flare & Particles

SOHO Instruments/EIT & LASCO

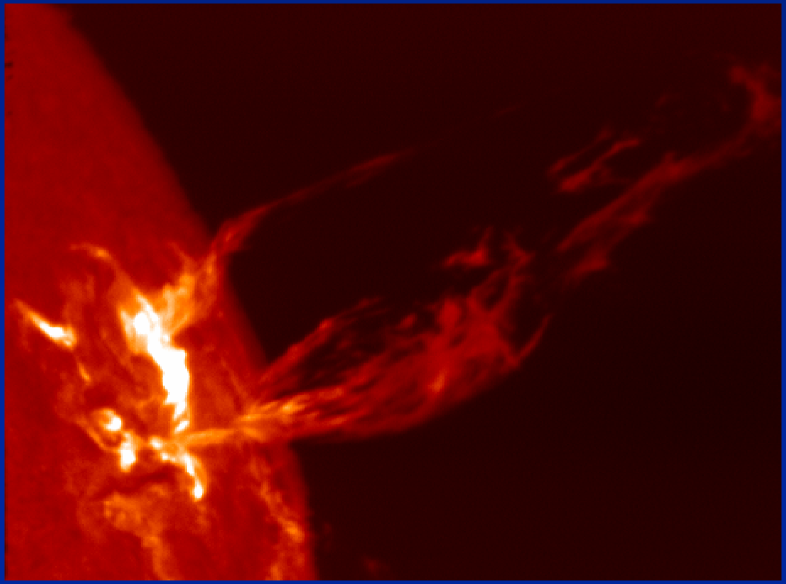


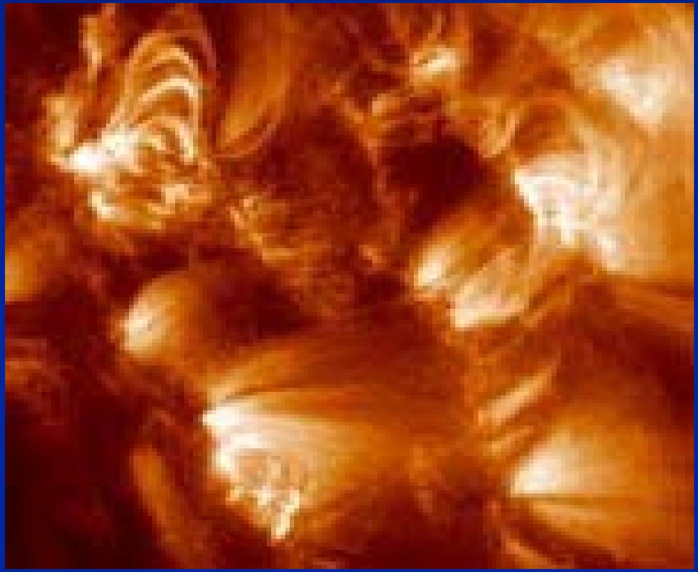
Solar flares are observed as sudden brightening near sunspots.

The solar system's largest explosive events.

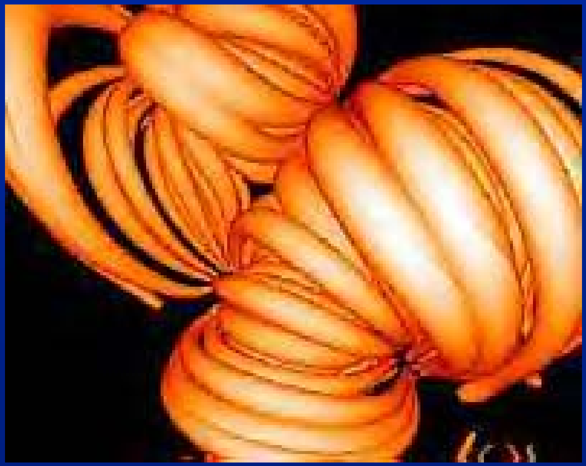
Particles are accelerated directly by event.

Coronal Mass Ejections

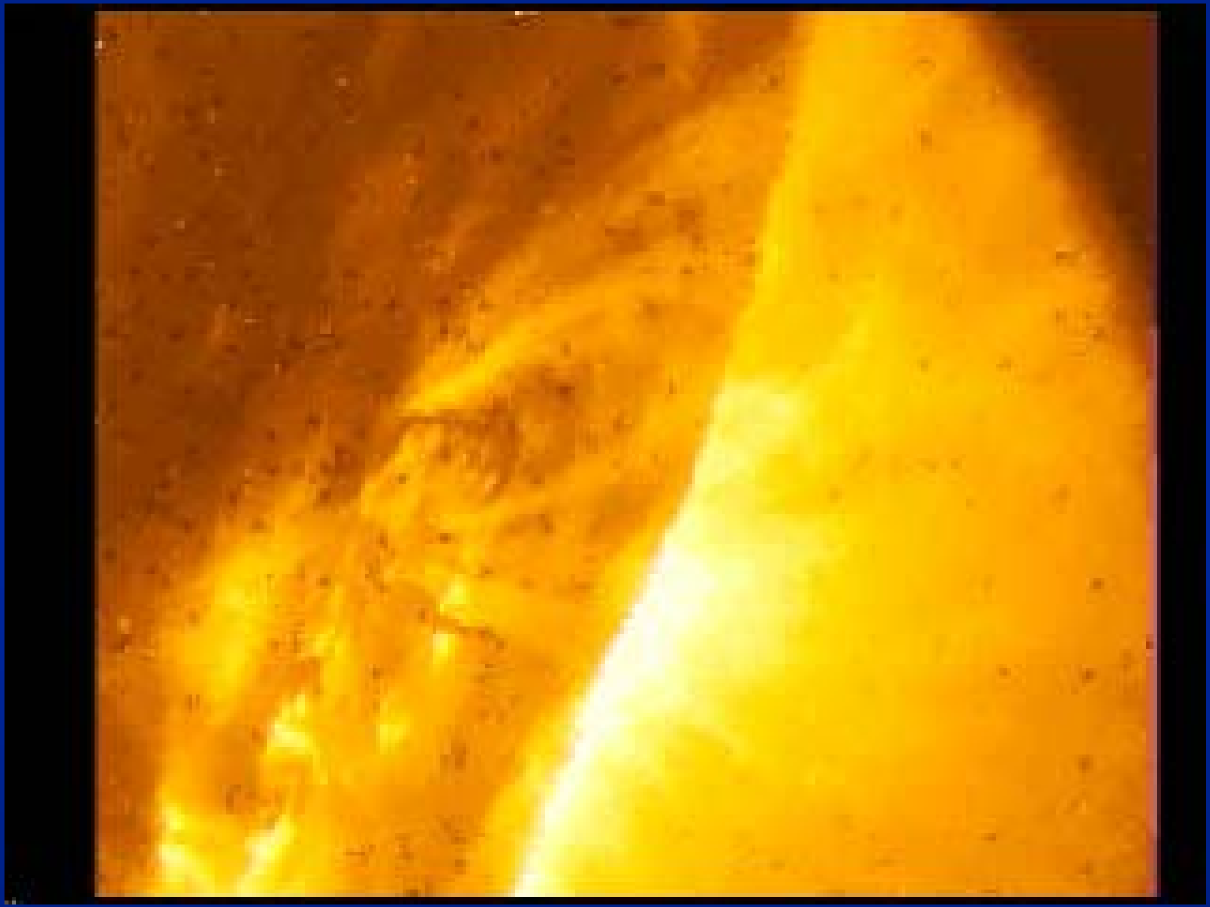




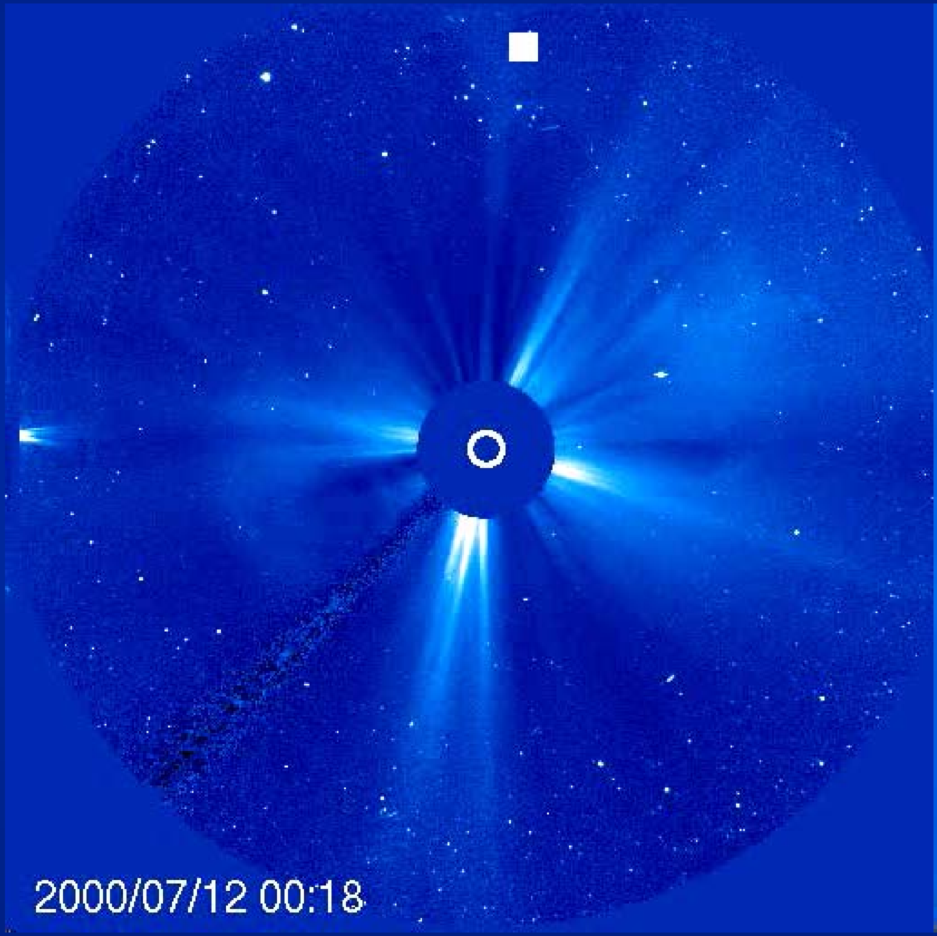
- Bubble of gas & magnetic field
- Ejects billions of tons of matter.
- Shock wave accelerates particles to millions of km/hr throughout the Solar System.



CME Movies – TRACE



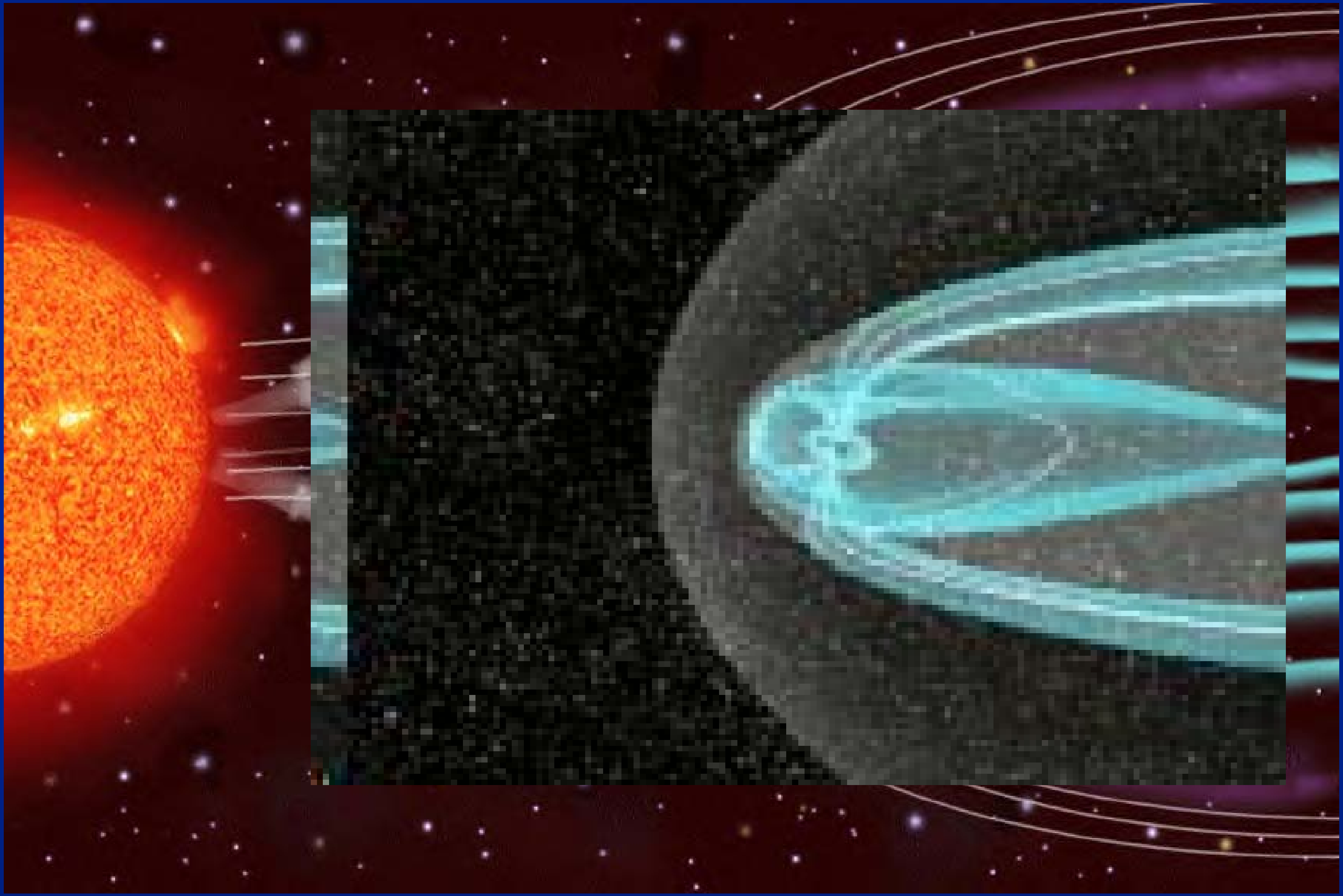
CME Movies – SOHO/LASCO



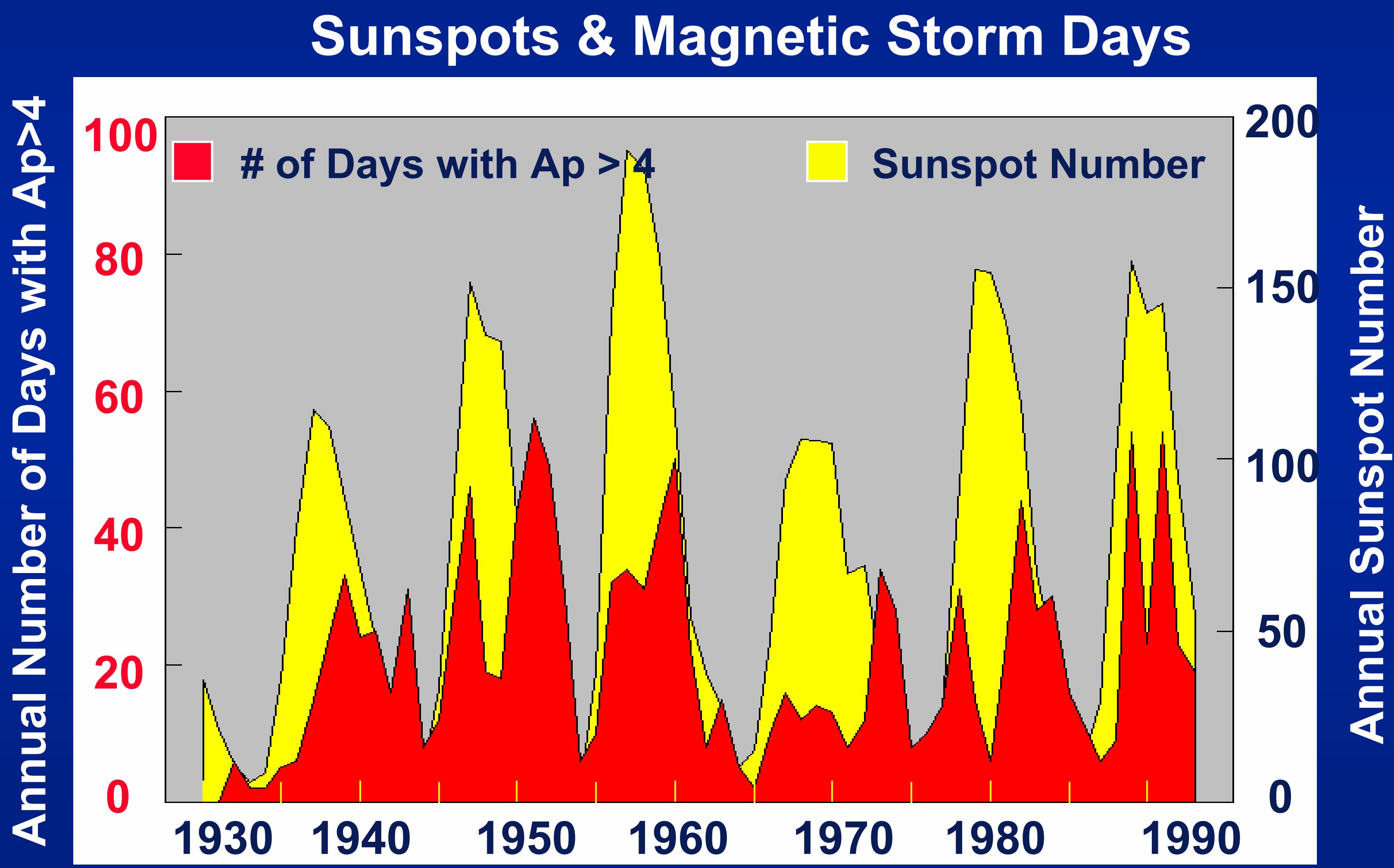
Magnetic Storms

- Major storms probably the result of CMEs
  - Must be pointed toward Earth
  - Strongest arrive with interplanetary magnetic field oriented south
- "Gusty" solar wind disturbs the current systems in the magnetosphere
- Cause increase in rate & intensity of magnetic sub-storms in the "tail" of the Earth's magnetosphere
  - Energizes and injects particles

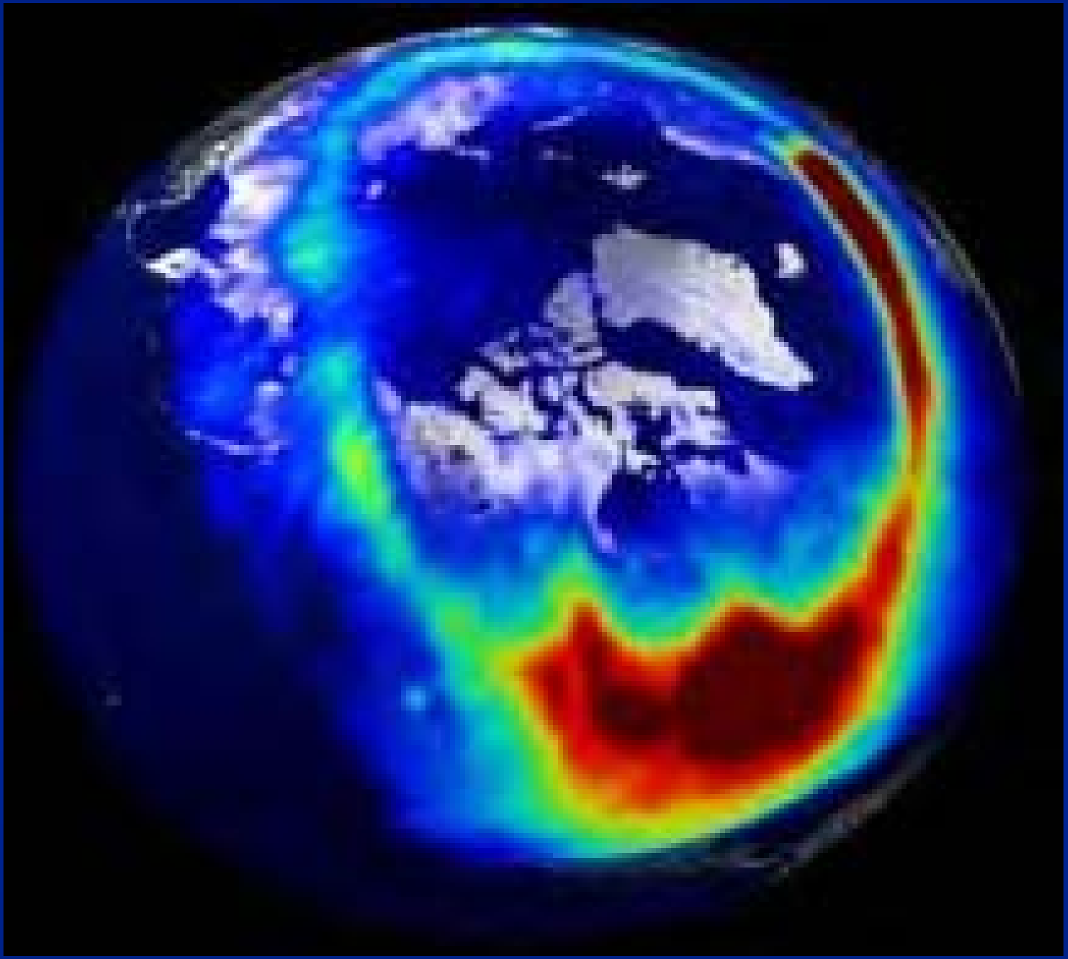
Effects of Storms on the Magnetosphere



Sunspot Cycle with Magnetic Storms



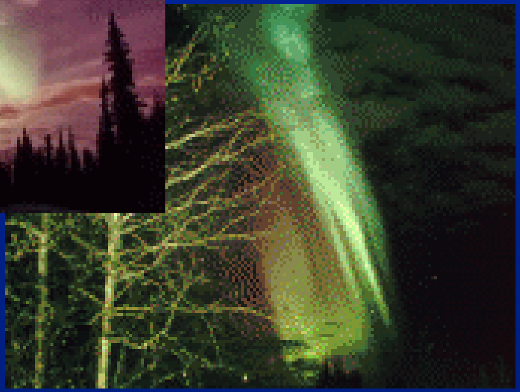
Particle Injections



Solar Storms cause particle injections at low latitudes.

Aurora

- Particles stream down on magnetic field lines from the geomagnetic tail forming an auroral belt.
- Electrons collide with atmospheric gases.
- Electrons give energy to atoms and molecules which emit energy as light.
- Oxygen ---> Green
- Nitrogen ---> Red



Space Environments

Description

Time Variations

Modeling Approach

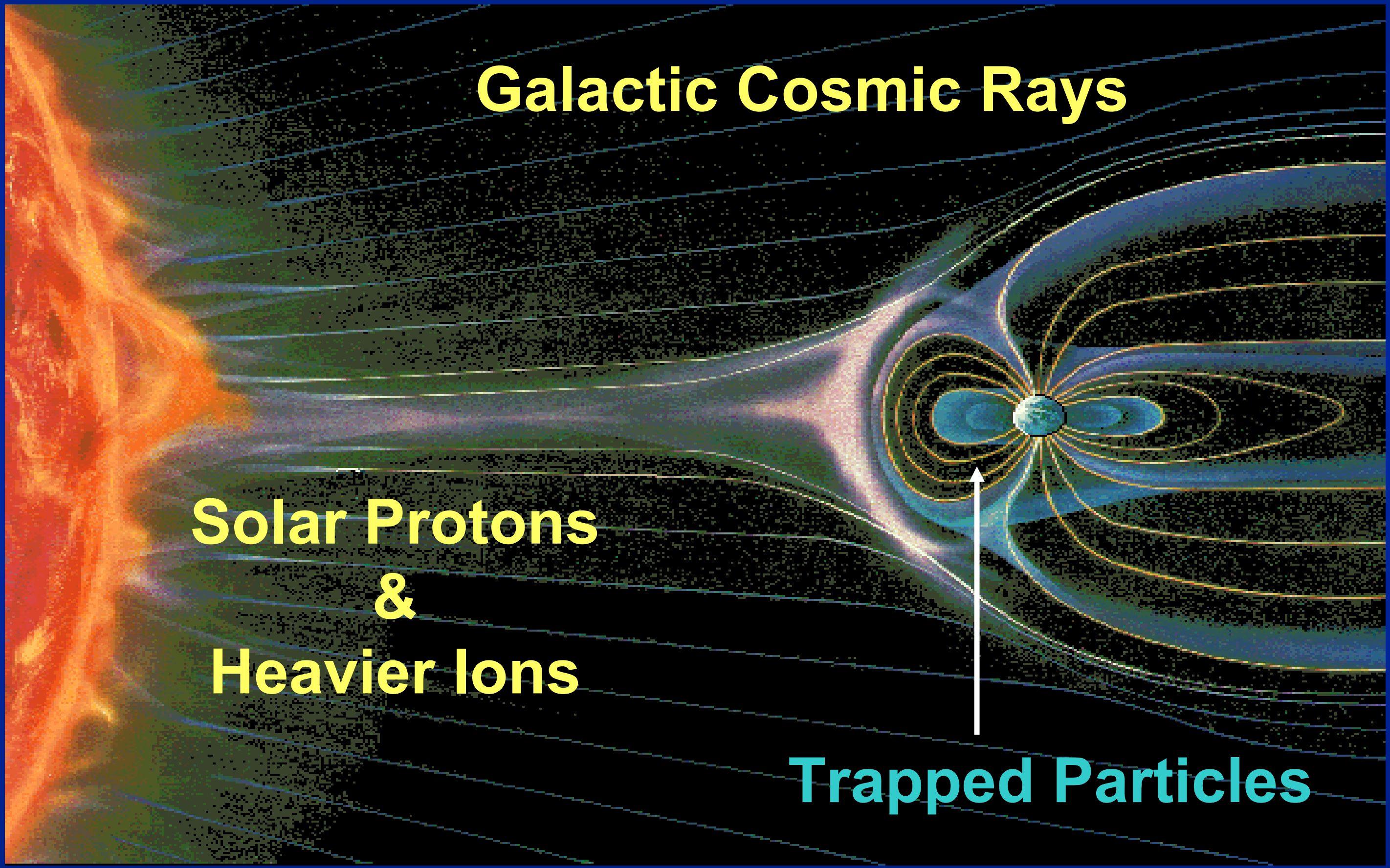
Energy Spectra

Spatial Distribution

Natural Environments

- Meteoroid & *Orbital Debris*
- Atmospheric Density & Composition
- Plasma
- Radiation Environment
- Electromagnetic Radiation
- Thermal Environment
- Geomagnetic Field
- Gravitational Field

High Energy Radiation Particles



Nikkei Science, Inc. of Japan, by K. Endo

Outline

- Heavy ions: He – U (2-92)
  - Galactic cosmic rays
  - Solar Particle Events (SPEs)
- Solar protons
- Trapped particles – Van Allen Belts
  - Protons
  - Electrons

Galactic Cosmic Ray Ions

- All elements in Periodic Table - 200 million years old
- Energies in GeV
- Found everywhere in interplanetary space
- Omnidirectional
- Mostly fully ionized - protons & bare nuclei of heavier elements
- Cyclic variation in fluence levels
  - Lowest levels = Solar Maximum peak
  - Highest levels = Lowest point in Solar Minimum
- Trajectories bent by magnetic field
- Single event effects hazard
- Model: CREME96 – Based on IMP-8 Data

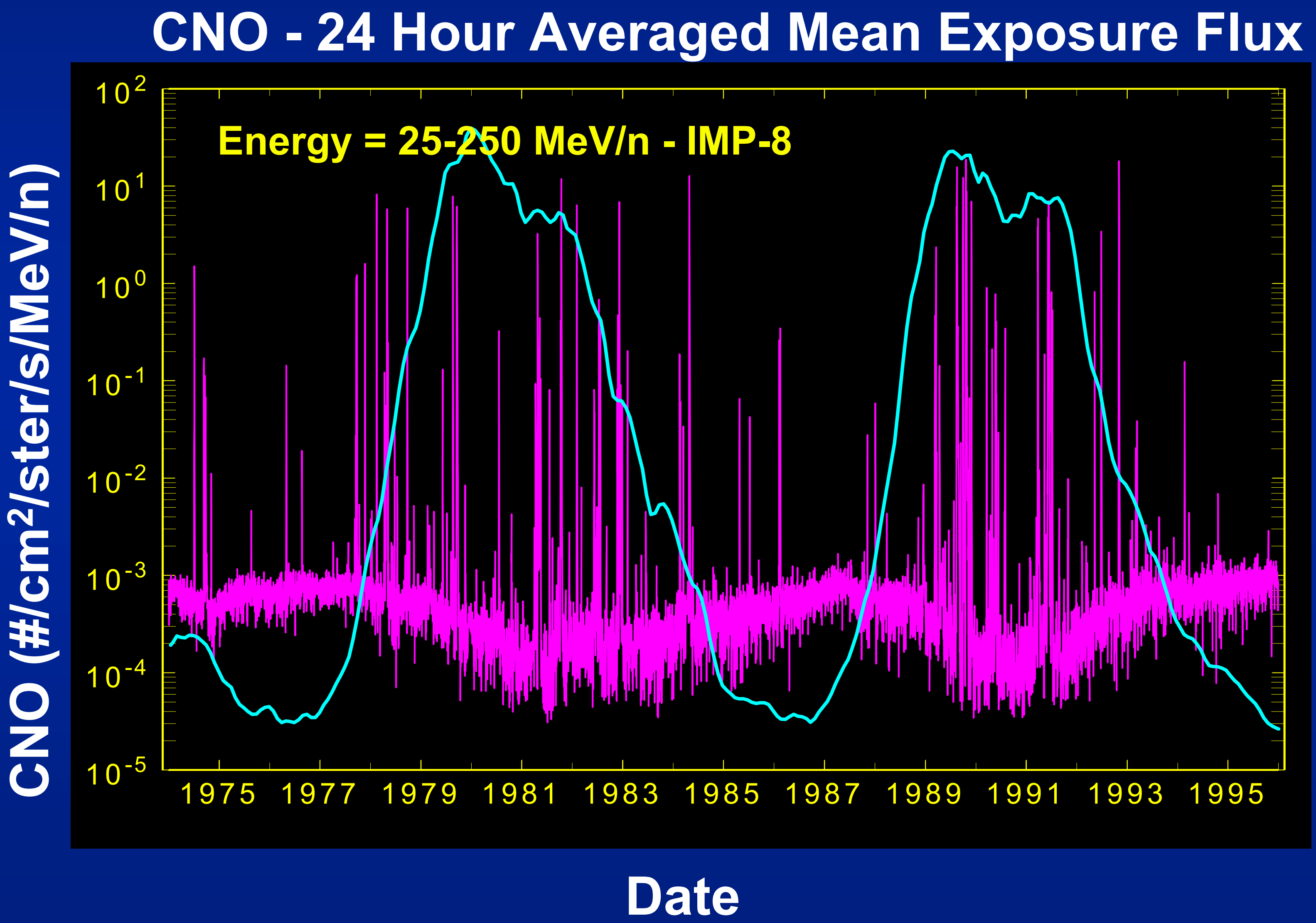
Discovery of Galactic Cosmic Rays - 1913

- Electroscope Experiments
  - Dissipation of Charge on Leaves?
  - Emissions from Materials on Earth
  - “Clean” Instruments Did Not Eliminate Dissipation
- Hess
  - Balloon Experiments with Electroscopes
  - Hypothesis: Background Radiation Will Disappear with Increasing Altitude
  - > 10,000 feet - Background Increased with Altitude
  - Named “Cosmic Rays” by Hess

Solar Particle Events

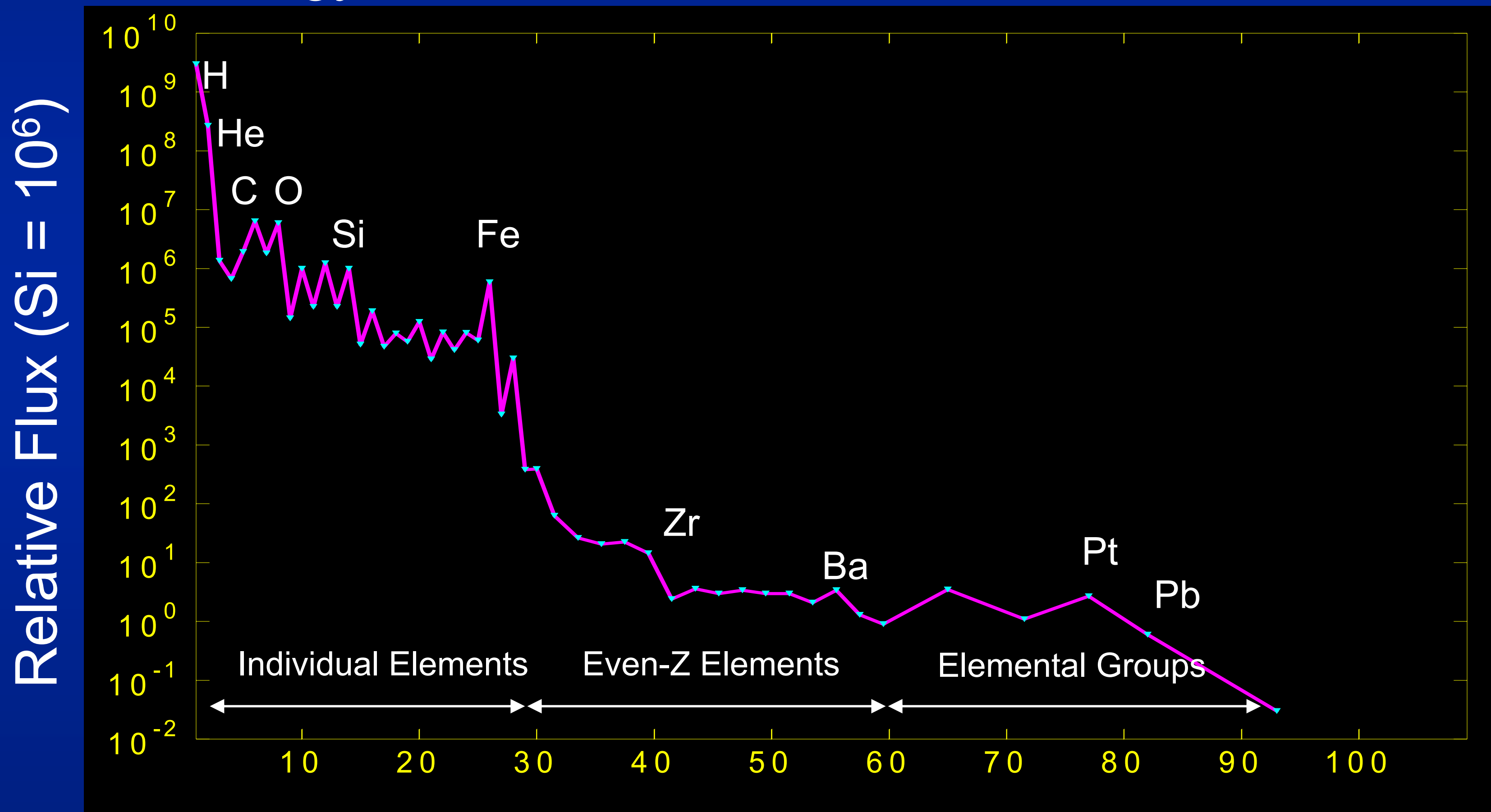
- Increased levels of protons & heavier ions
- Energies
  - Protons - 100s of MeV
  - Heavier ions - 100s of GeV
- Abundances dependent on radial distance from Sun
- Partially ionized - greater ability to penetrate magnetosphere
- Number & intensity of events increases dramatically during Solar Maximum
- Models
  - Dose - SOLPRO, JPL, ESP/GSFC&NRL
  - Single Event Effects - CREME96 (Protons & Heavier Ions)

Heavy Ion Population



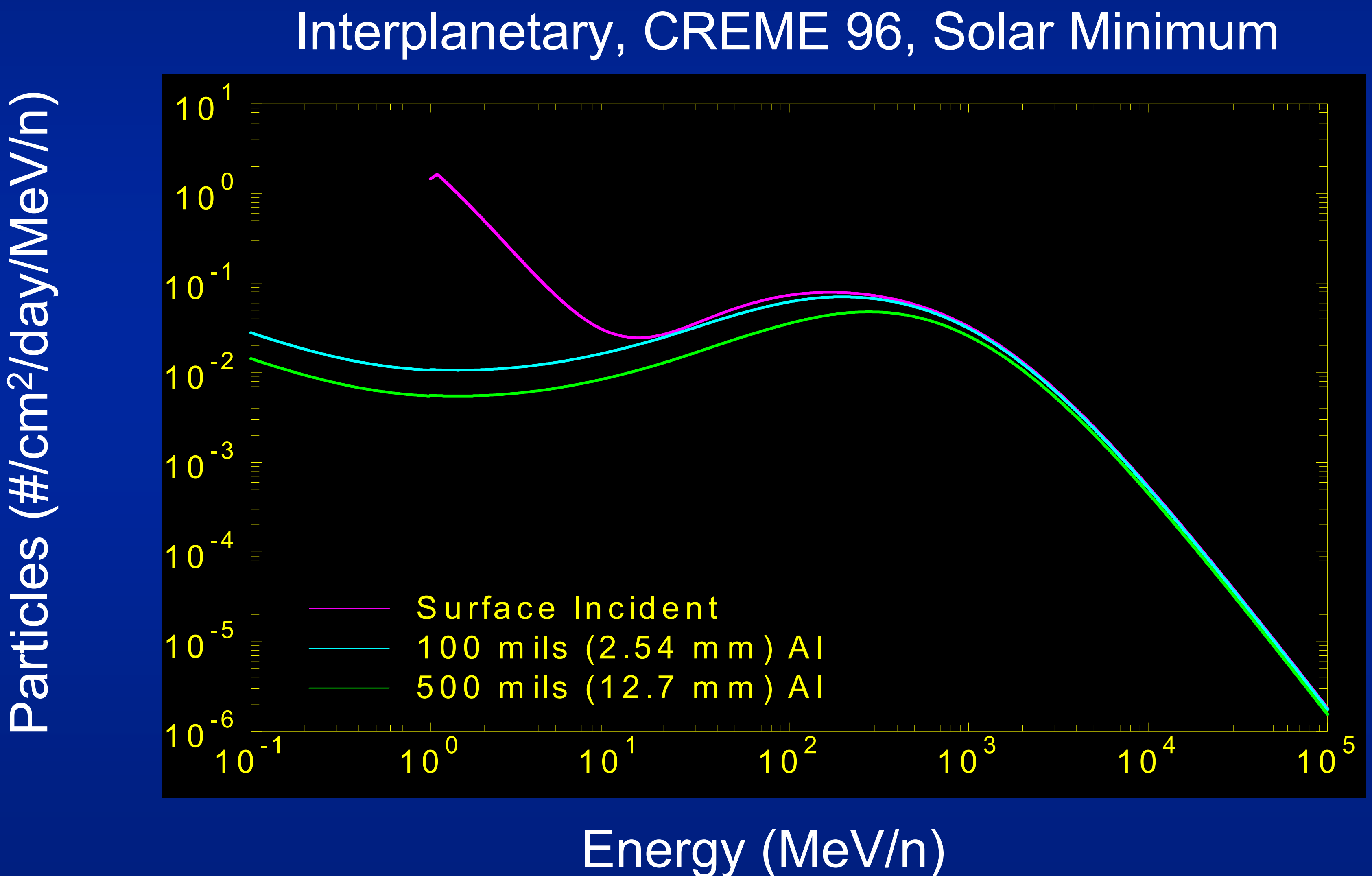
GCRs: Nuclear Composition

Energy = 2 GeV/n, Normalized to Silicon = 10^6

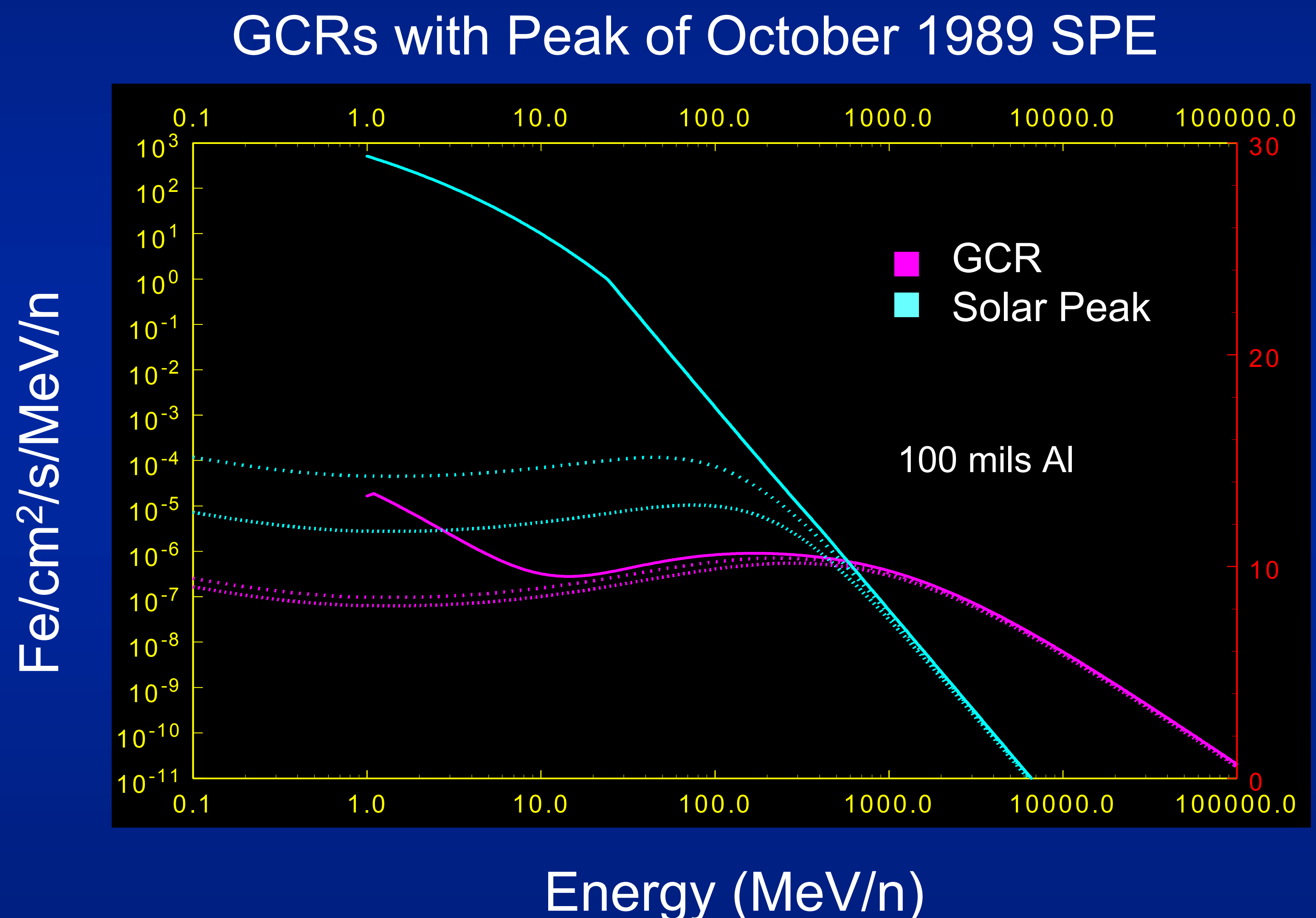


Nuclear Charge (Z)

GCRs: Shielded Fluences - Fe

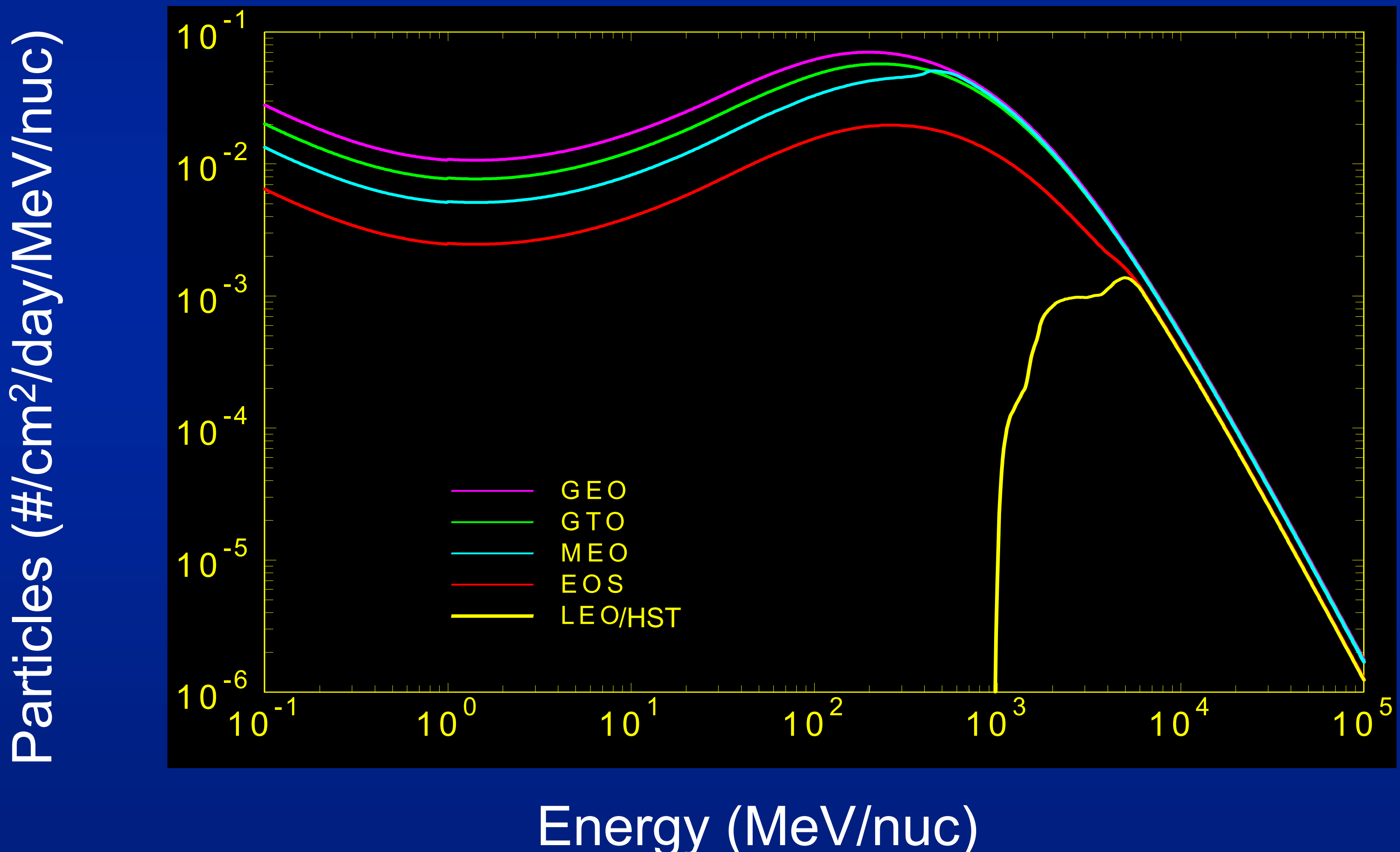


SPEs: Shielded Fluences - Fe



The Magnetospheric Filter - Fe

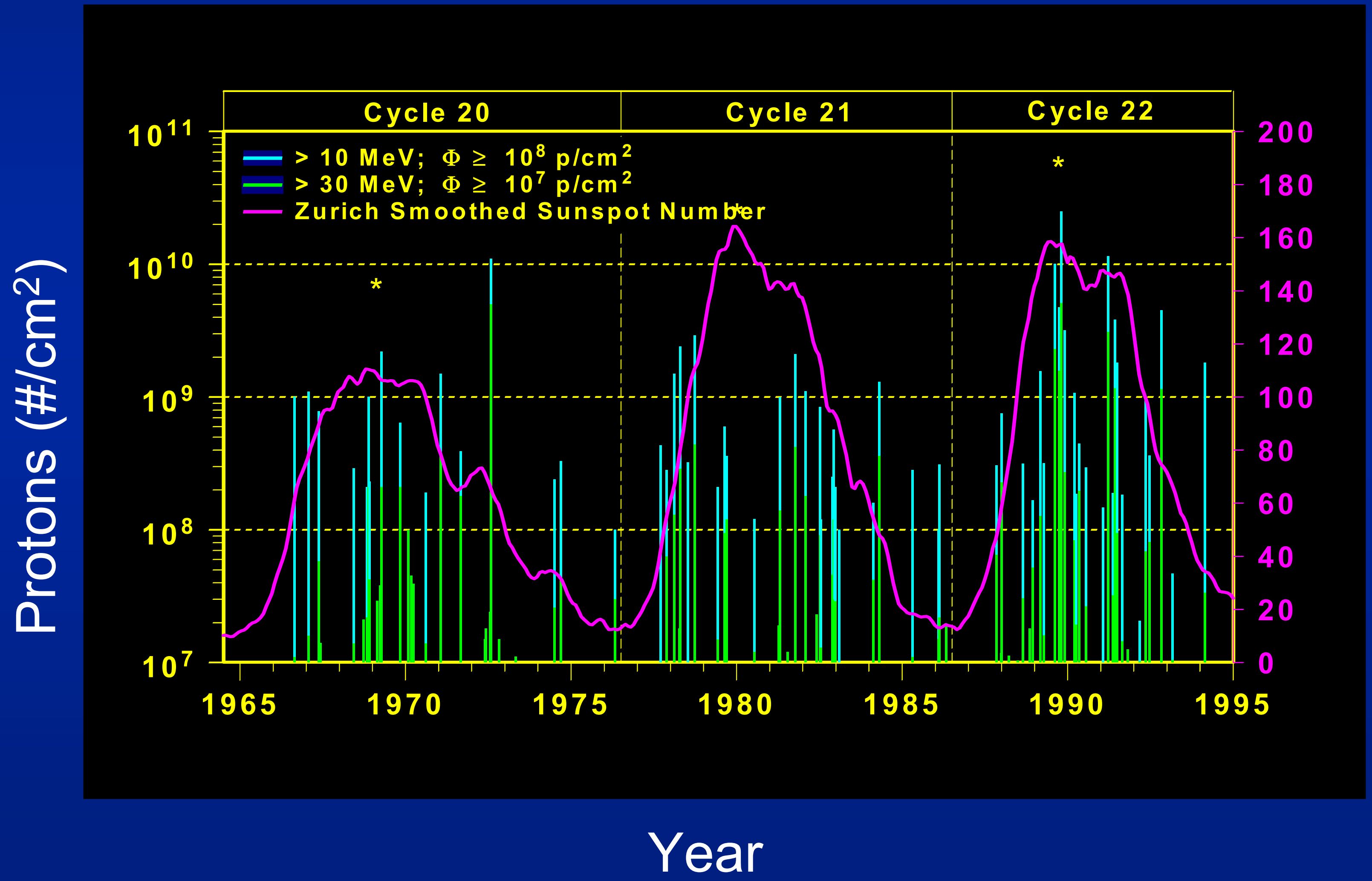
CREME 96, Solar Minimum, 100 mils (2.54 mm) Al



Solar Protons

Solar Protons

Proton Event Fluences

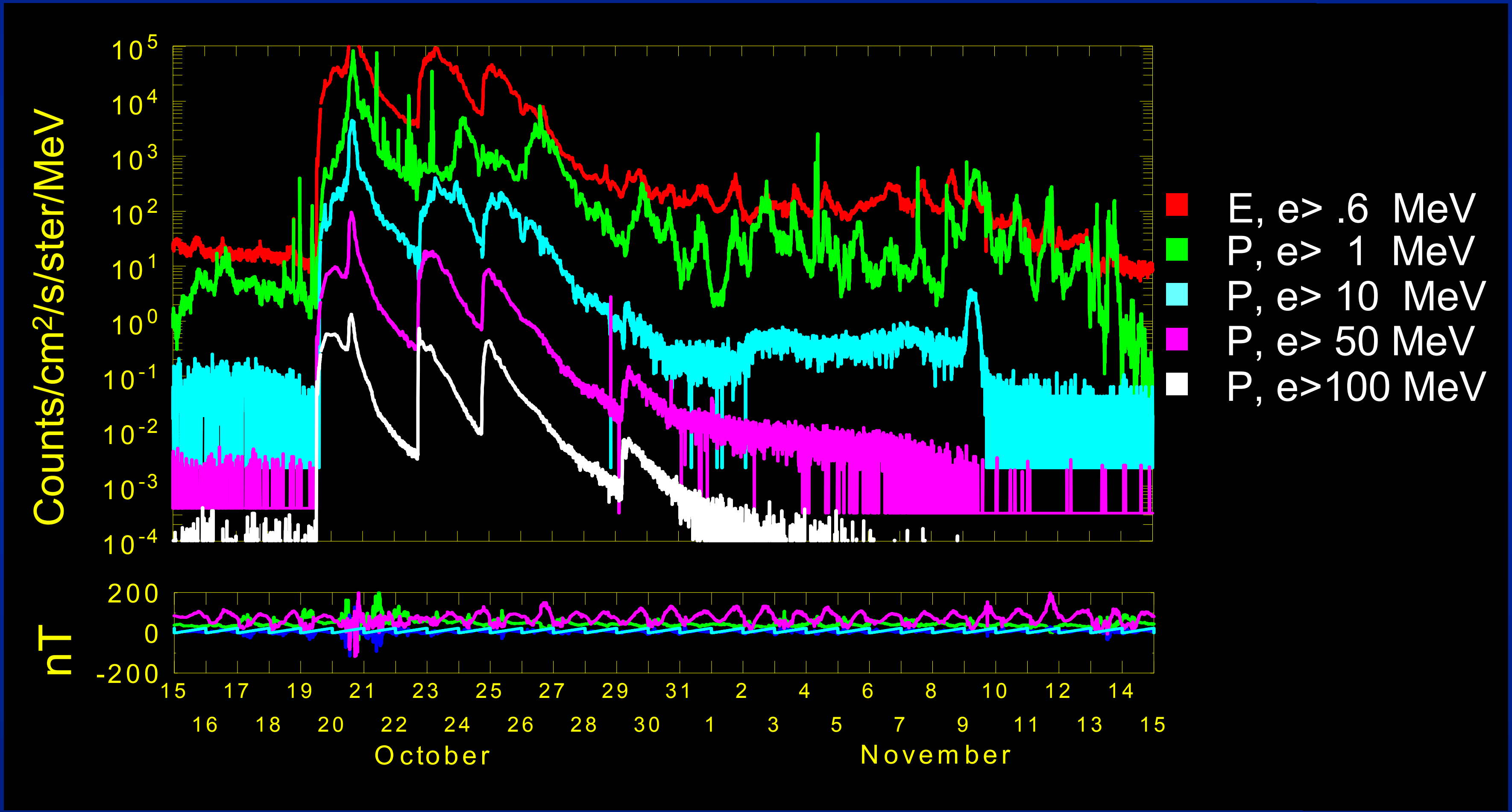


J. Barth/Code 561

14 February 2002

Solar Protons - October 1989 Event

Protons & Electrons - Magnetic Field



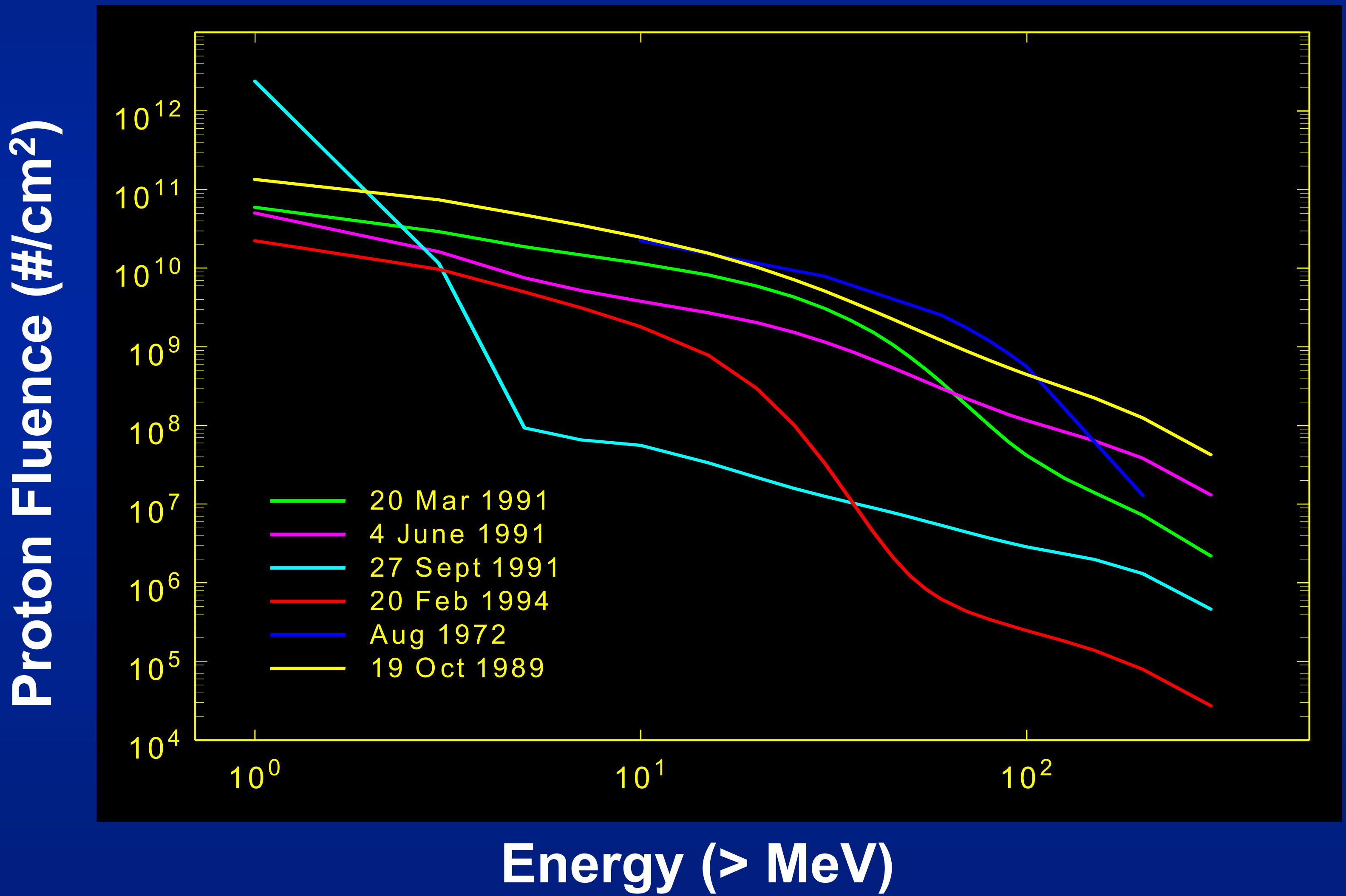
GOES Space Environment Monitor

J. Barth/Code 561

14 February 2002

Spectra from Solar Proton Events

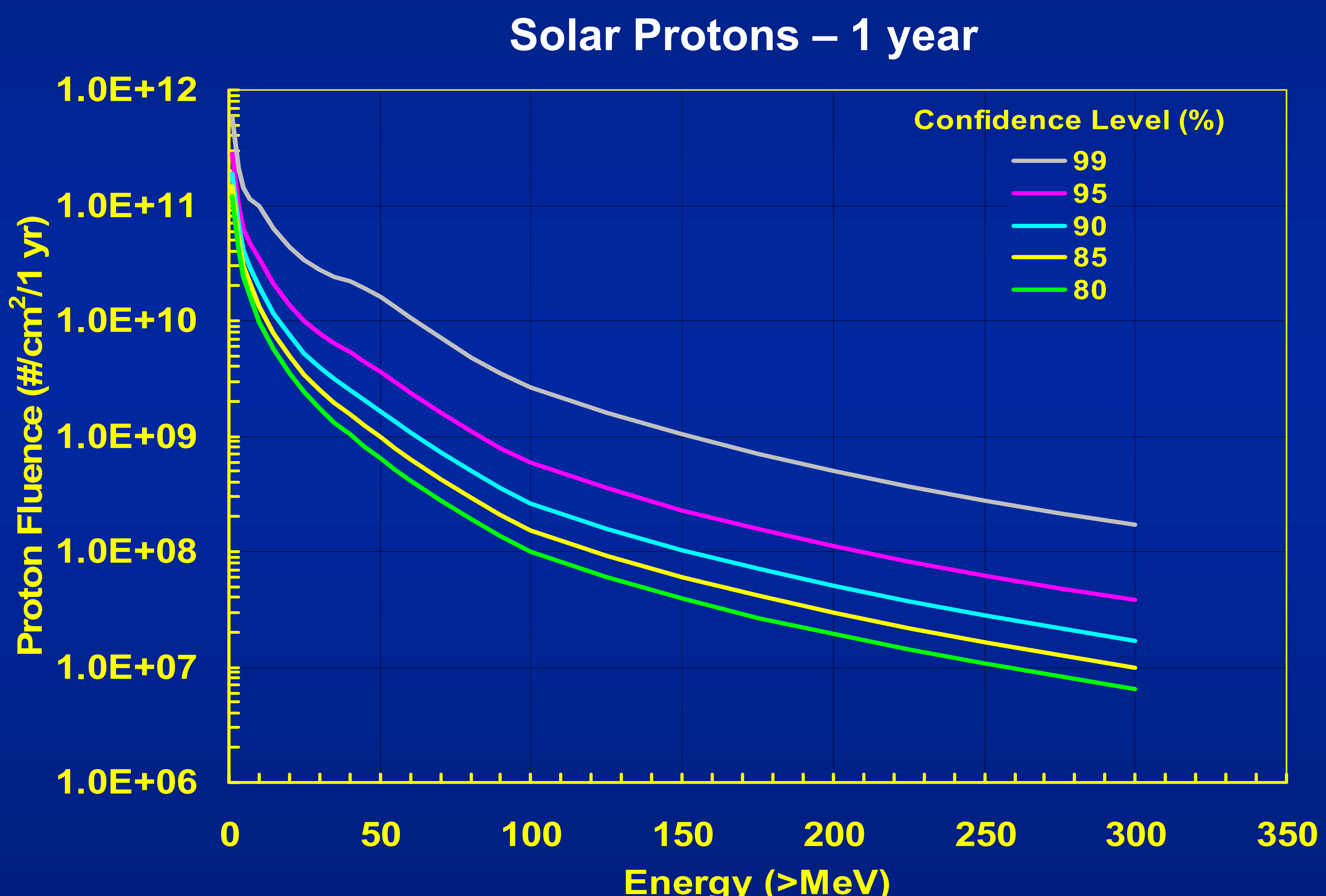
Total Solar Proton Fluence for Selected Events



Modeling Approach

- Use IMP & GOES proton data
- Define statistical engineering model
  - » Intensity as a function of mission duration & confidence level
  - » Does not predict when events occur
- Apply Maximum Entropy Principle - incomplete dataset
  - » Determines frequency distribution of large solar proton events
  - » Frequency distribution consistent with other complex physical phenomena such as earthquakes
- Apply Extreme Value Theory
  - » Determines upper limit for occurrence of huge events
  - » New upper limit consistent with data sets dating back to ancient times - Lunar Rock Record
- Predicted fluence levels are non-linear in time and confidence level

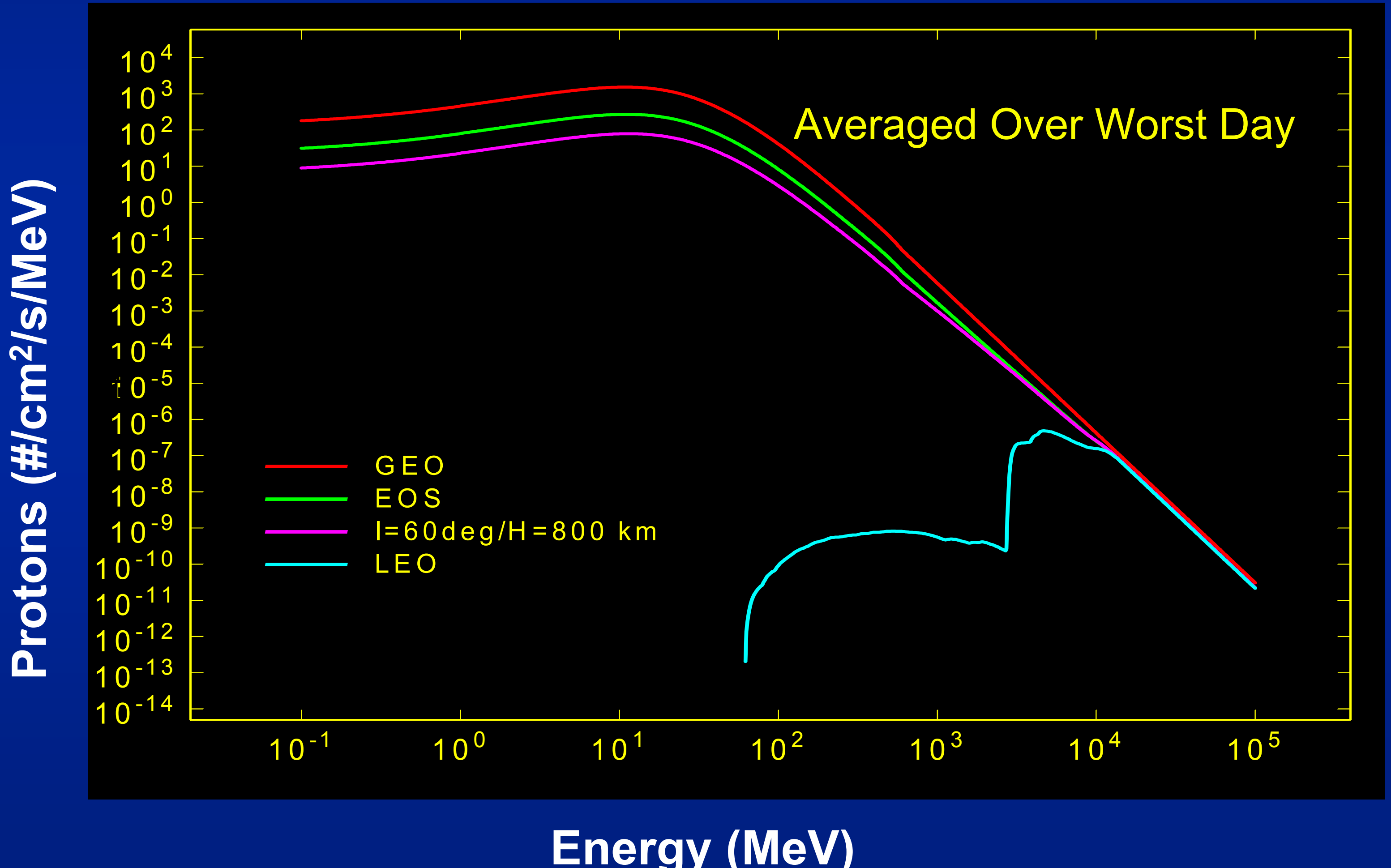
ESP Model



Solar Protons – 1 year
Proton Fluence (#/cm2/1 yr)
Energy (>MeV)
Confidence Level (%)
99
95
90
85
80
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
0
50
100
150
200
250
300
350

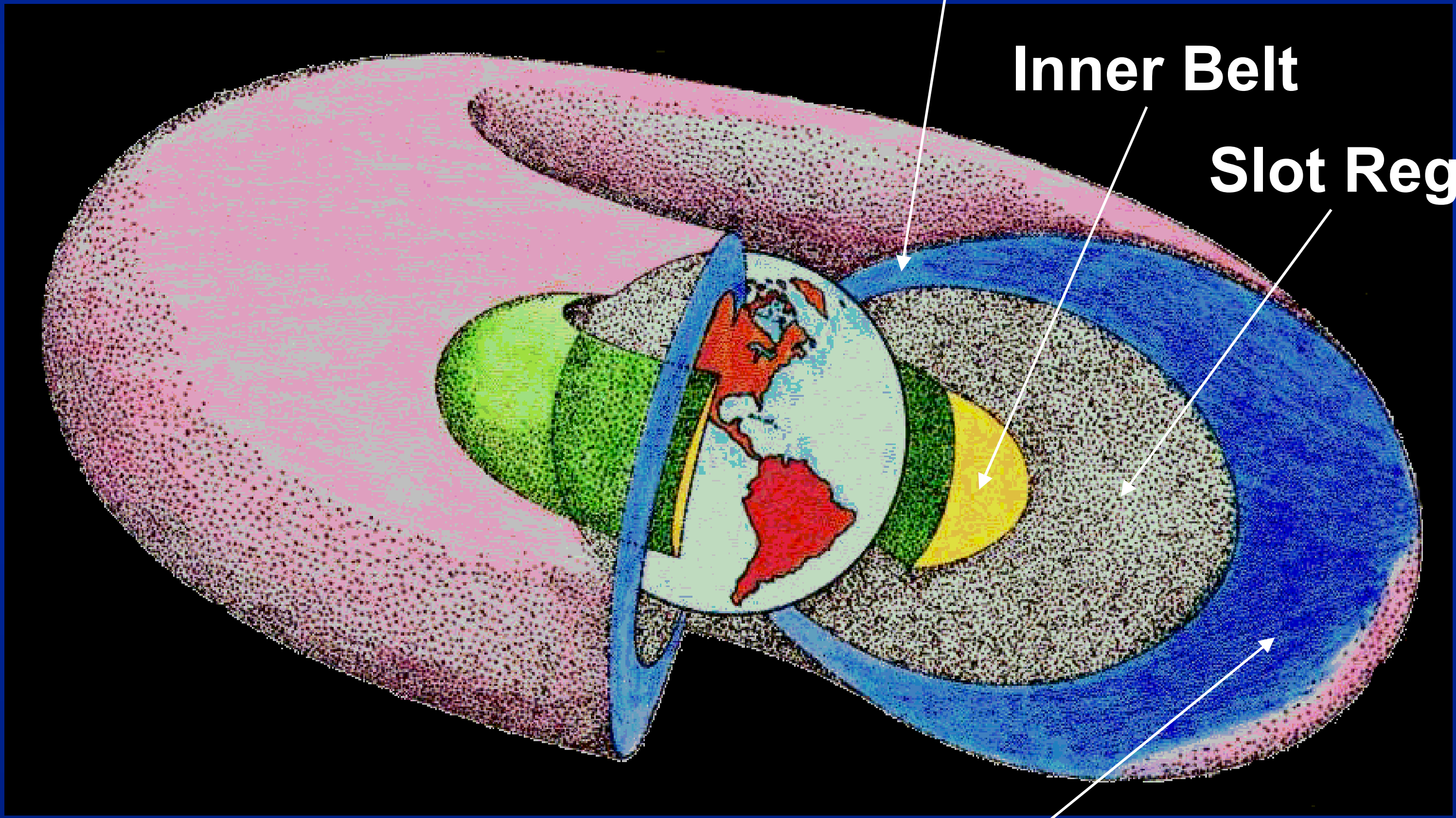
Solar Protons: Orbits

Proton Levels Predicted by CREME 96



Trapped Particles

Van Allen Belts



BIRA/IASB

Trapped - Van Allen Belts

- Omnidirectional
  - » Anisotropy at inner edge (300-500 km) 2 ~ 7
- Components
  - » Protons: E ~ .04 - 500 MeV
  - » Electrons: E ~ .04 - 7(?) MeV
  - » Heavier Ions: Low E - non-problem for electronics
- Population levels vary by location
  - » Orders of magnitude
  - » Steep gradients in some locations
- Location of peak levels depends on energy
- Average counts vary slowly with the solar cycle
- Storm effects
- Models – AP-8, AE-8, NOAA-PRO, CRRESPRO, CRRESELE

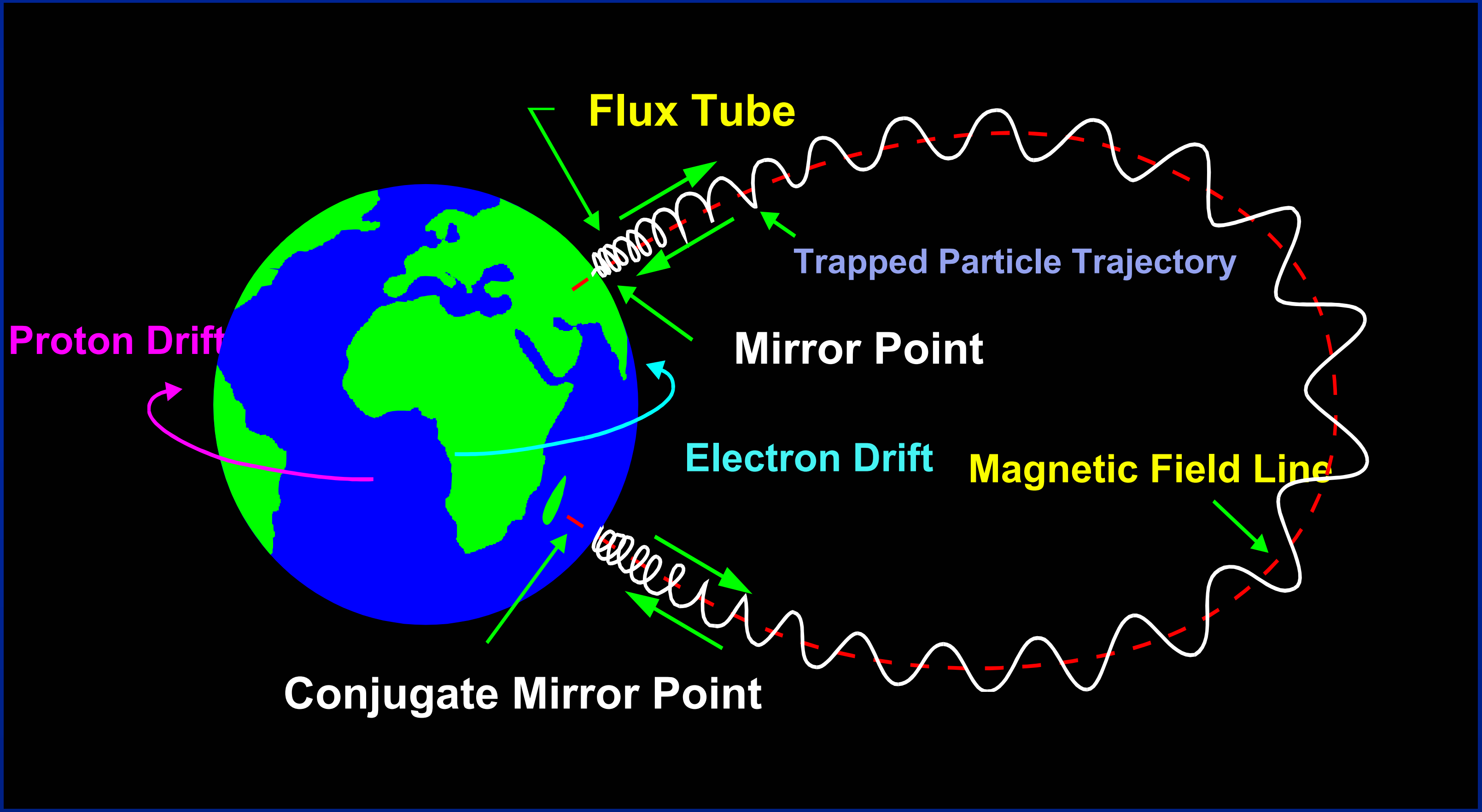
Particle Cascades in Atmosphere

- Collisions between cosmic rays & atmospheric O & N
- CRAND – Comic Ray Albedo Neutron Decay

- Residual neutrons
  - » Single Event Upsets
    - – Shuttle
    - – Aircraft
    - – Ground
  - » Passenger & crew exposure in aircraft

Trapped Particle Motions

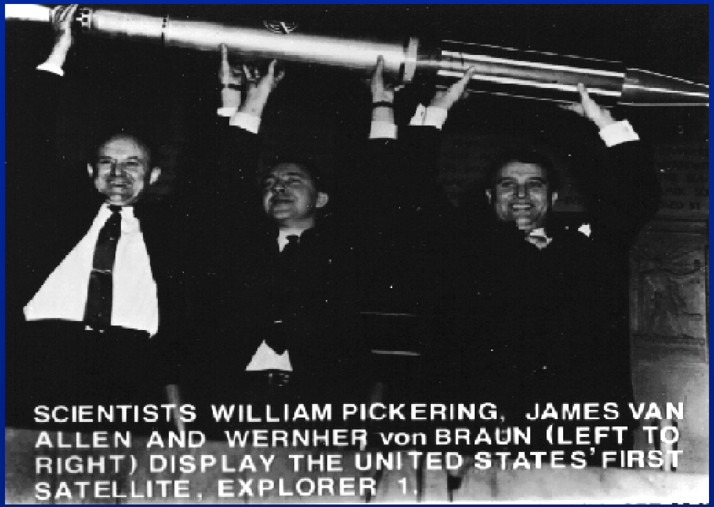
Spiral, Bounce, Drift



after Hess

Discovery of the Radiation Belts

- James Van Allen
  - » First observation of auroral electrons with a rocket
  - » Cosmic ray detector
- Highlight of US participation in IGY



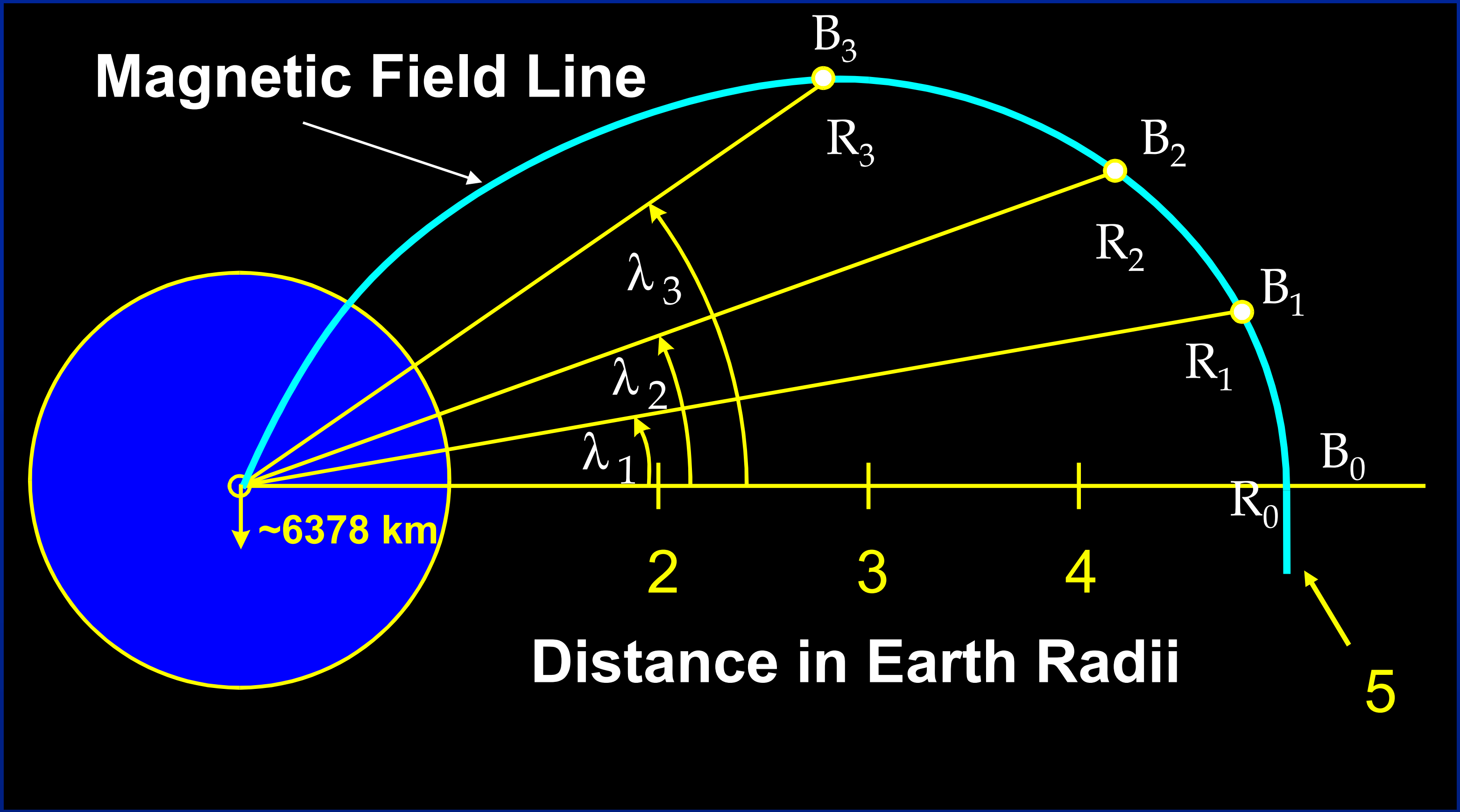
Charged Particle Motion

- Birkeland - 1895
  - Vacuum chamber experiments to study aurora
  - With Poincare showed that charged particles spiraled around field lines and are repelled by strong fields
- Stöermer -
  - Continued work of Birkeland on aurora
  - Calculations led to theory that there was a belt-like area around the earth in which particles were reflected back and forth between the poles
- Singer (U. o f Md) - 1957
  - Proposed that ring current could be carried by lower energy particles injected by into trapped orbits by magnetic storms
- Christofilos
  - Study of particle motion in magnetic fields - Project Argus

B-L Coordinate System - Dipole

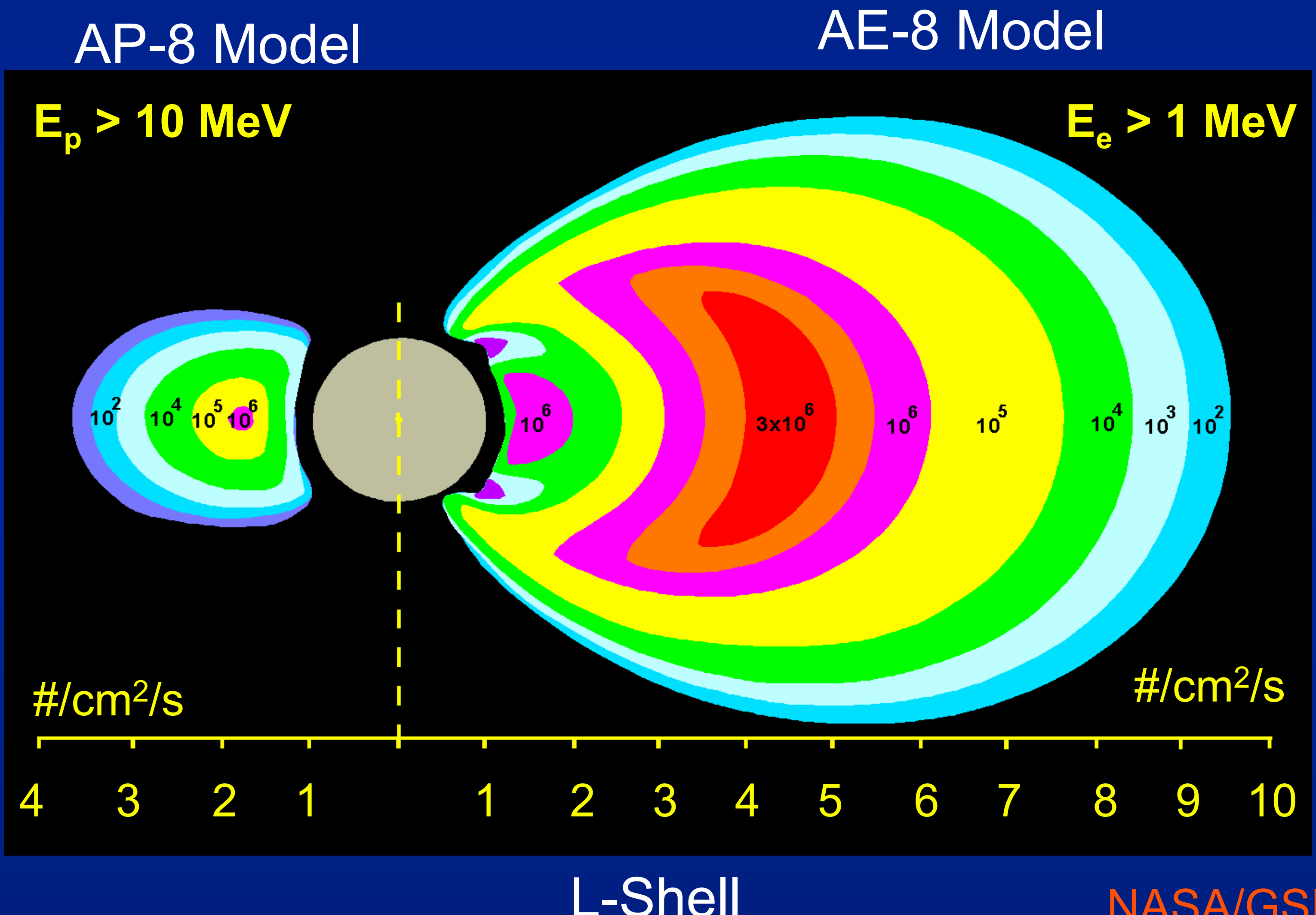
B - Magnetic Field Strength

L - Distance at Equatorial Crossing in Earth Radii



after Stassinopoulos

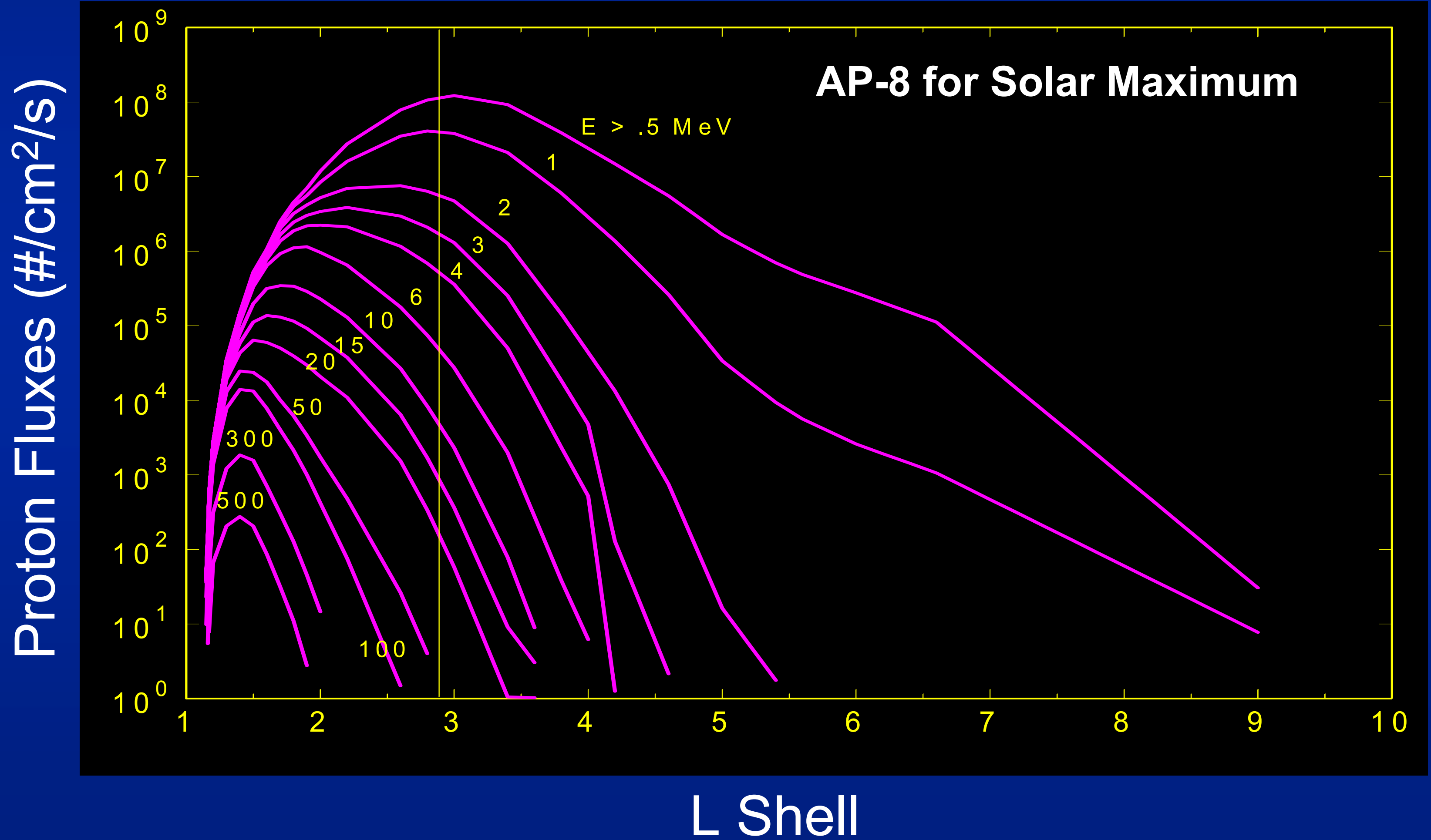
Proton & Electron Intensities



NASA/GSFC

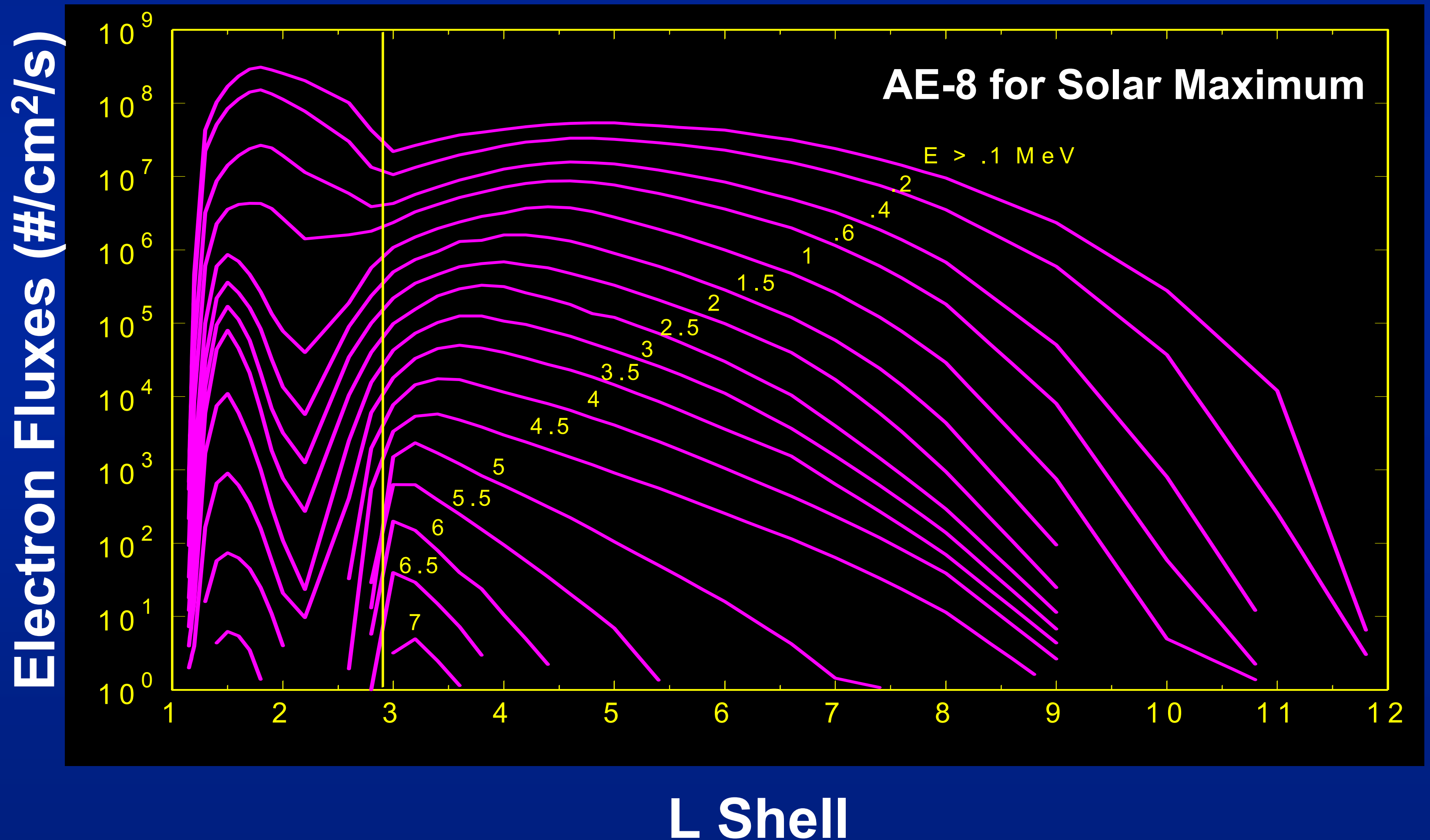
AP-8 Model Fluxes vs. L

Integral Proton Fluxes at Magnetic Equator



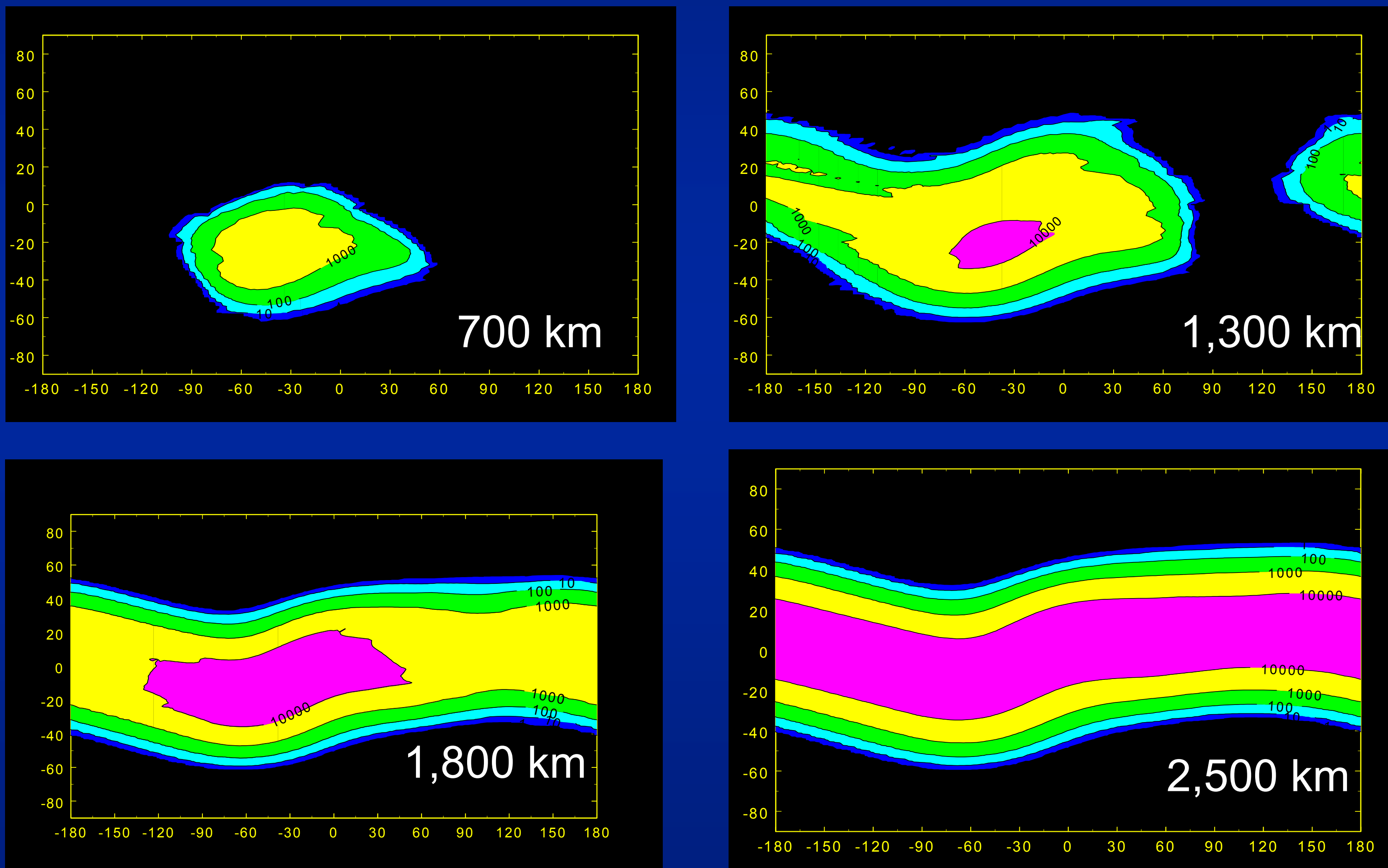
AE-8 Model Fluxes vs. L

Integral Electron Fluxes at Magnetic Equator



Trapped Protons – AP-8

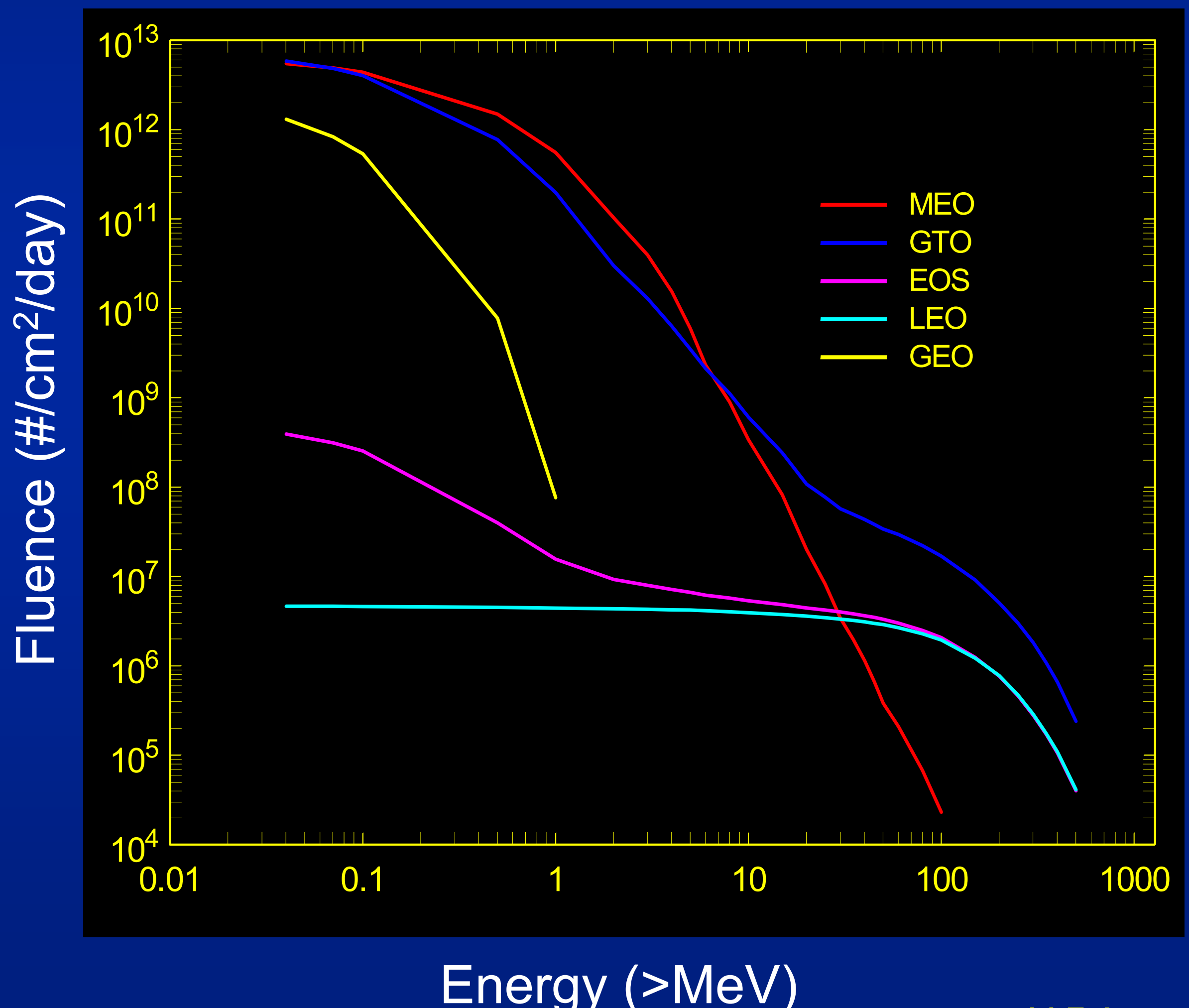
E > 30 MeV (#/cm²/s) - Solar Minimum



AP8 - MAX Spectra

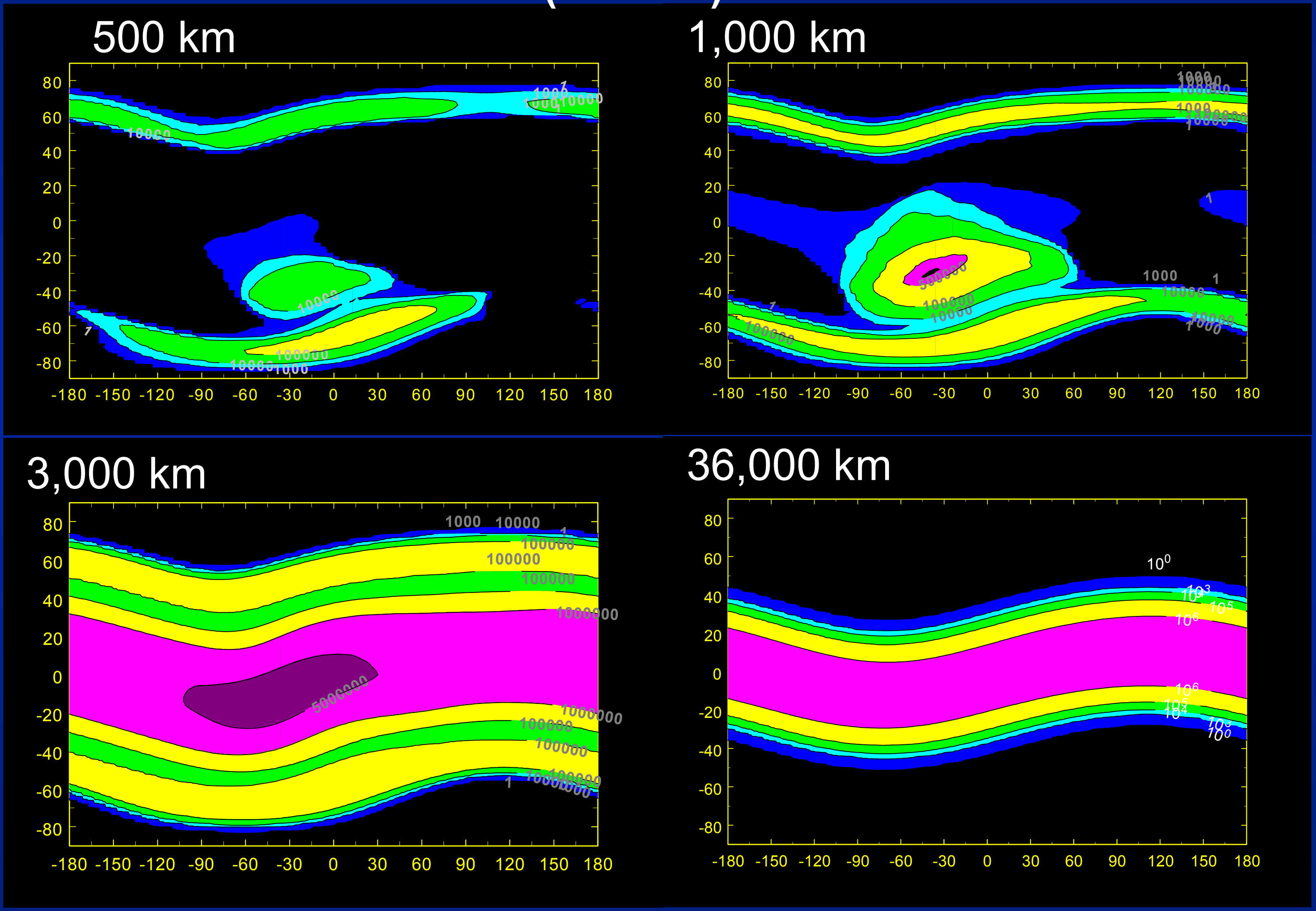
- Energy Range
  - » .04 - 500 MeV
- Range in Al:
  - » 30 MeV ~ .17 inch
- Effects:
  - » Total dose
  - » Single event effects
  - » Solar cell damage
  - » Displacement damage

Integral Proton Fluences



Trapped Electrons – AE-8 Solar Minimum

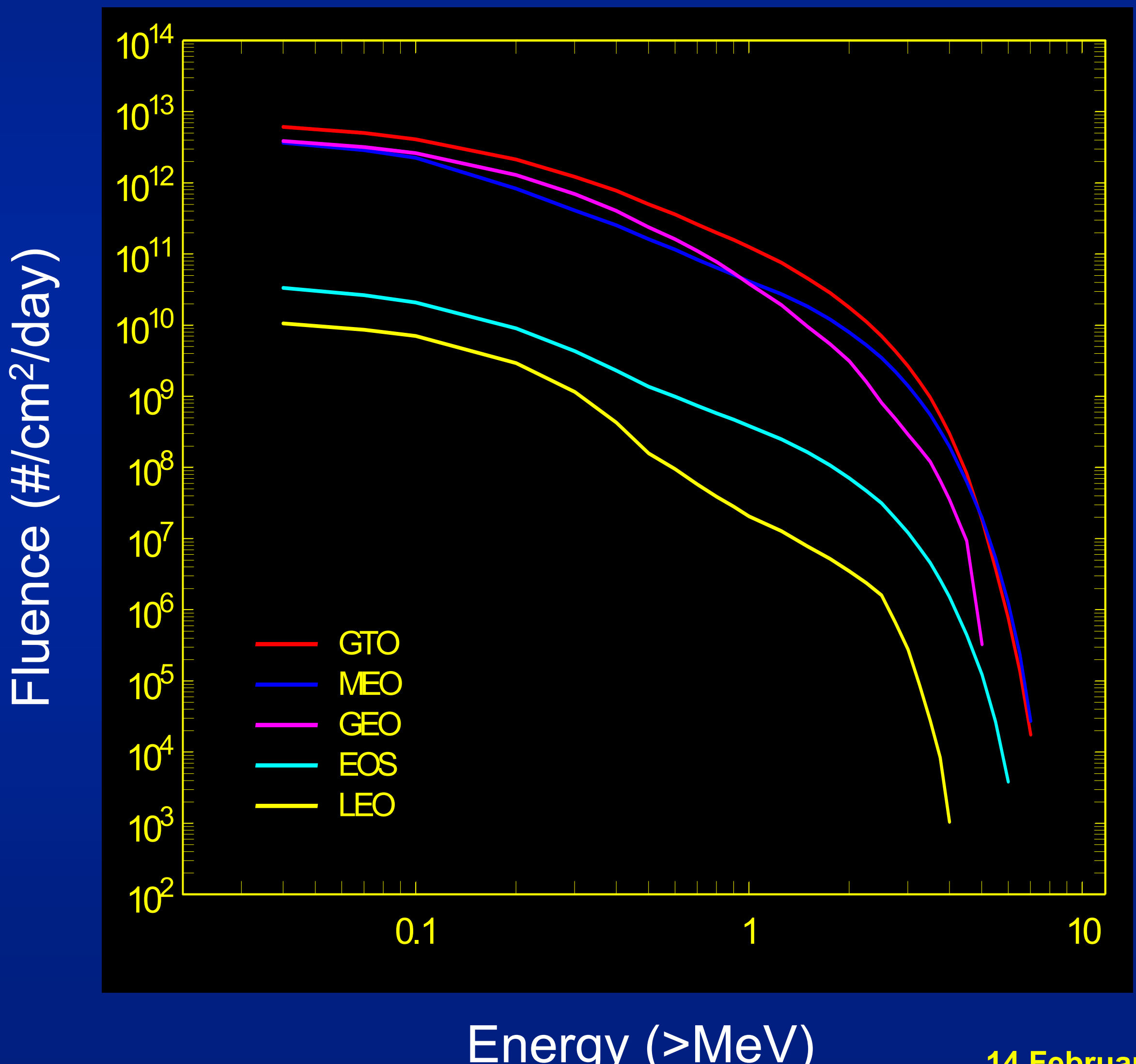
E > 0.5 MeV (#/cm²/s) - Solar Minimum



AE-8 - MAX Spectra

- Energy Range
  - .04 - 10 MeV
- Range in Al:
  - 1 MeV ~ .08 inch
- Effects:
  - Total dose
  - Surface charging
  - Deep dielectric charging
  - Solar cell damage

Integral Electron Fluences

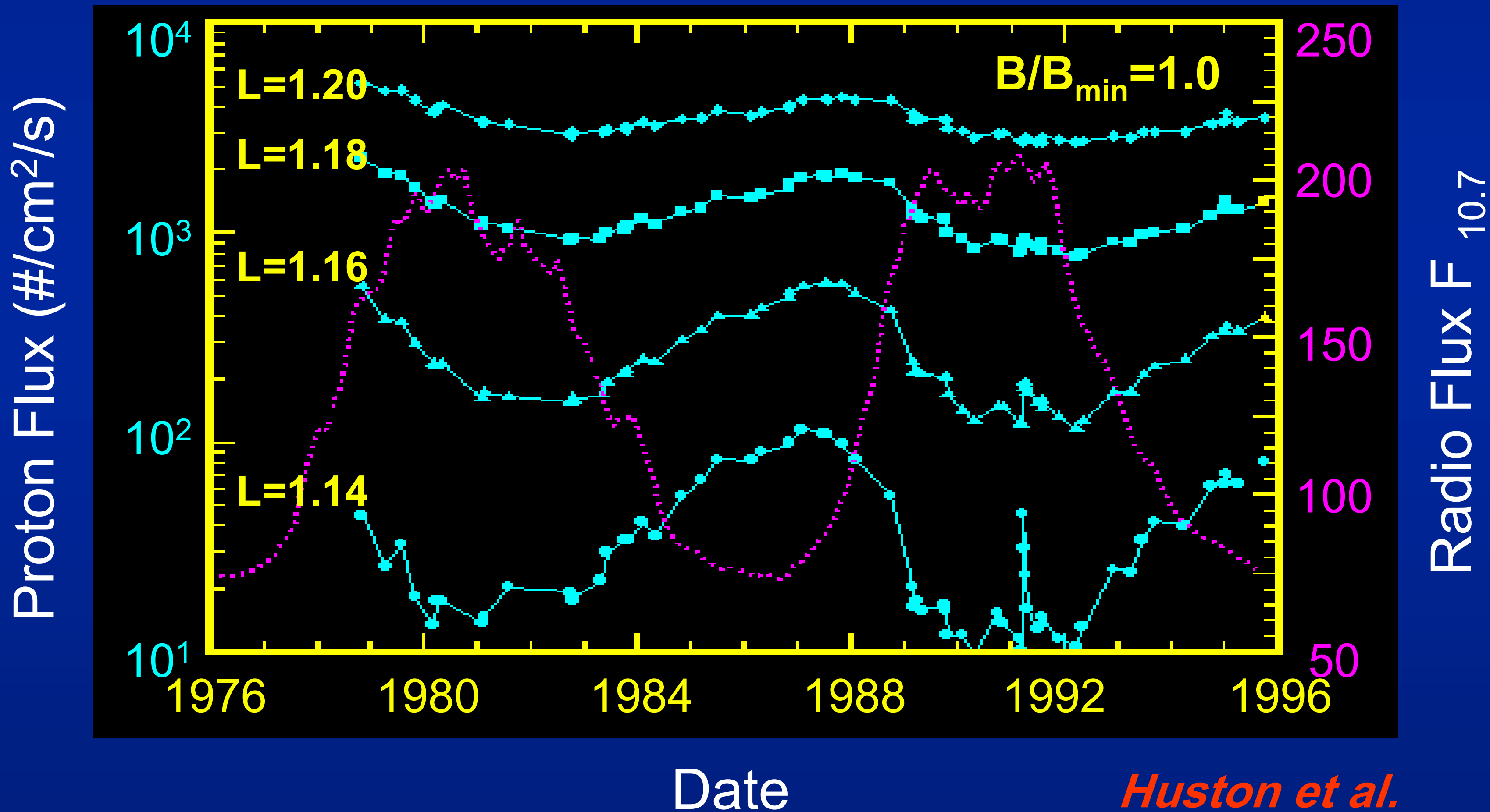


Time Variations - Protons

- Relatively stable - averages vary slowly with time
- Cyclic modulations due to the solar cycle ~ 2
  - Lowest levels are near the peak of solar maximum.
  - Highest levels are near lowest point in solar minimum.
  - Rate of change ~ 6%/year
- Geomagnetic field shift changes location of SAA
  - ~ 6 ° westward / 20 years
- Storm effects
  - Production of new belts – solar proton injection
  - Sudden increases in particle levels – orders of magnitude

TIROS/NOAA - Trapped Protons

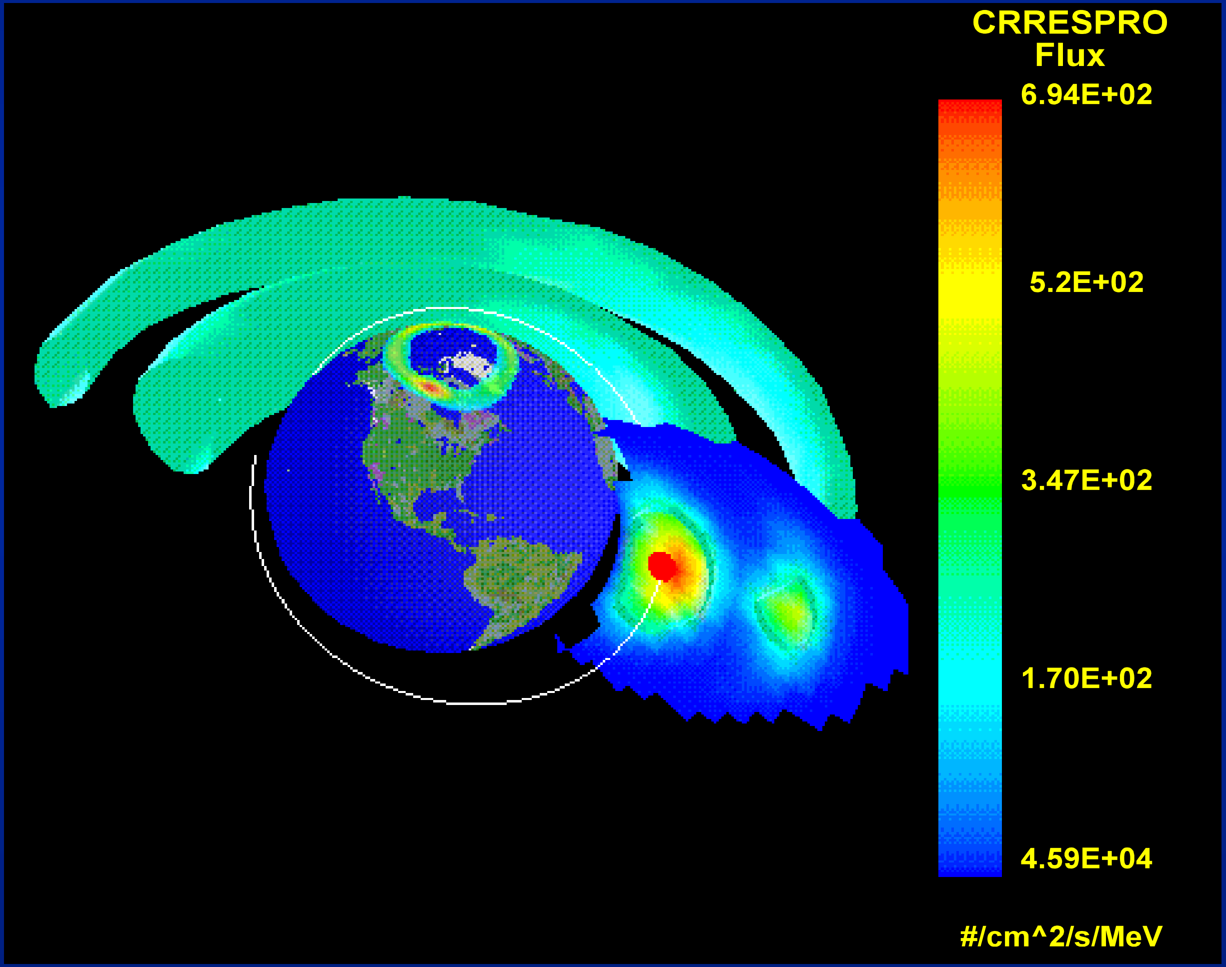
Solar Cycle Variation: 80-215 MeV Protons



Huston et al.

CRRES - Measured Proton Belt

March 1991



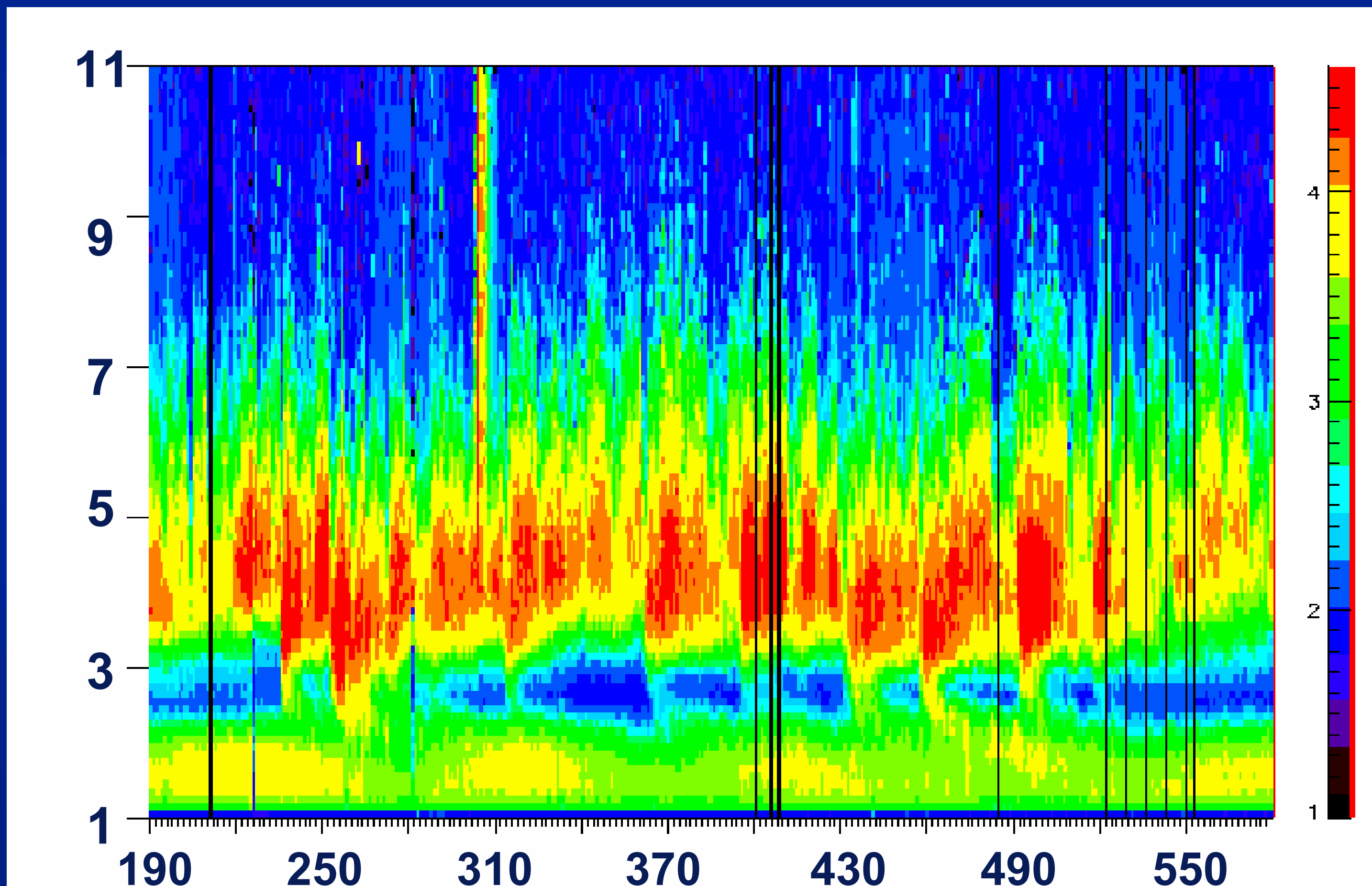
AF Phillips Laboratory, SPD/GD

Time Variations - Electrons

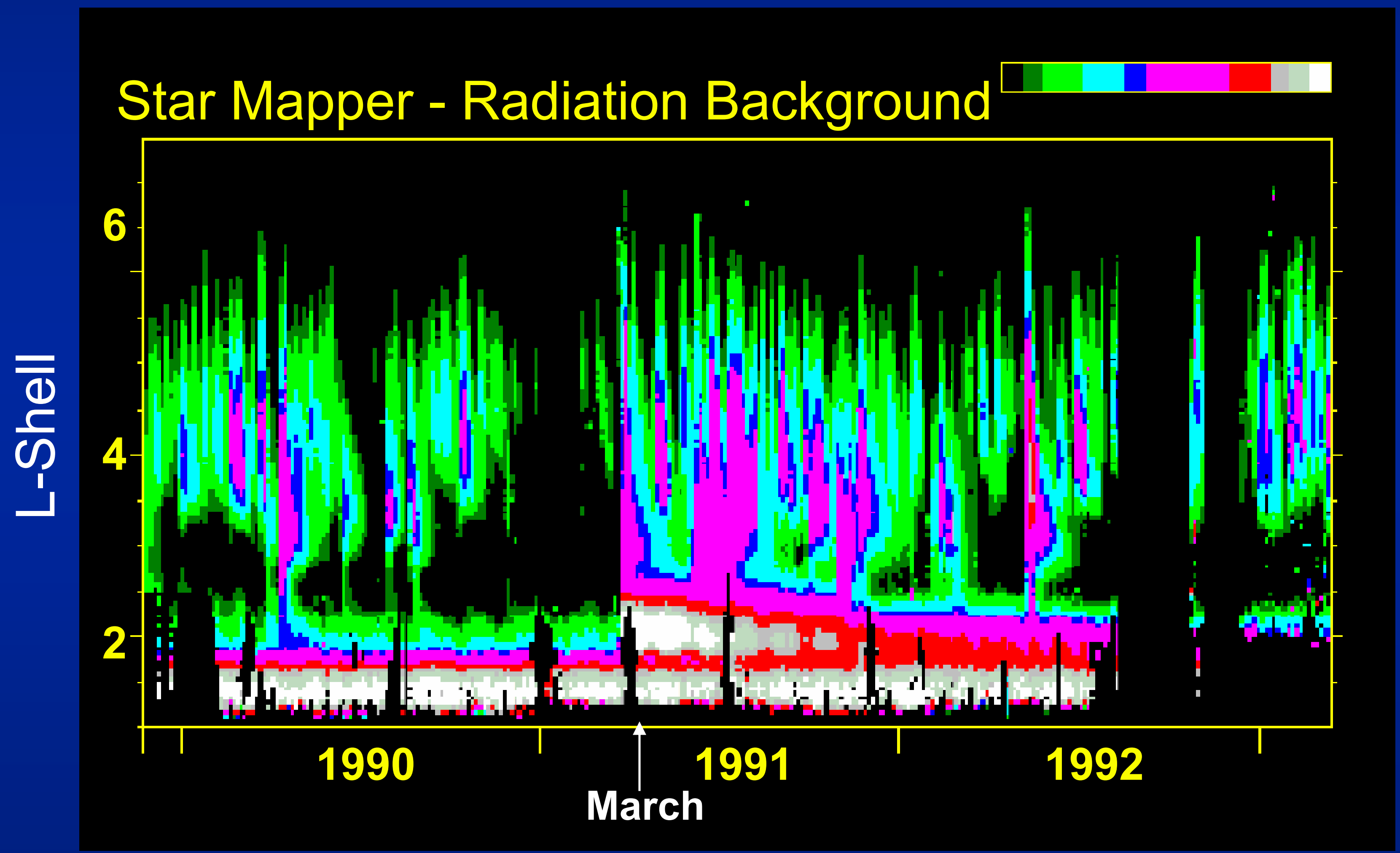
- Cyclic modulation due to the solar cycle ~ 2
  - Highest levels are near peak of solar maximum
  - Lowest levels are near lowest point in solar minimum
- Inner Zone - fairly stable
- Outer Zone - Dynamic $10^2 \sim 10^6$
  - Solar cycle variations are masked
  - Local time variations due to magnetic field distortion
  - 27-Day variation due to solar rotation
- Storm effects
  - Production of new belts – accelerated electrons
  - Sudden increases in particle levels – orders of magnitude

Electron Variability in Outer Zone

SAMPEX/P1ADC: Electrons E > 0.4 MeV



Magnetic Storms - Hipparcos

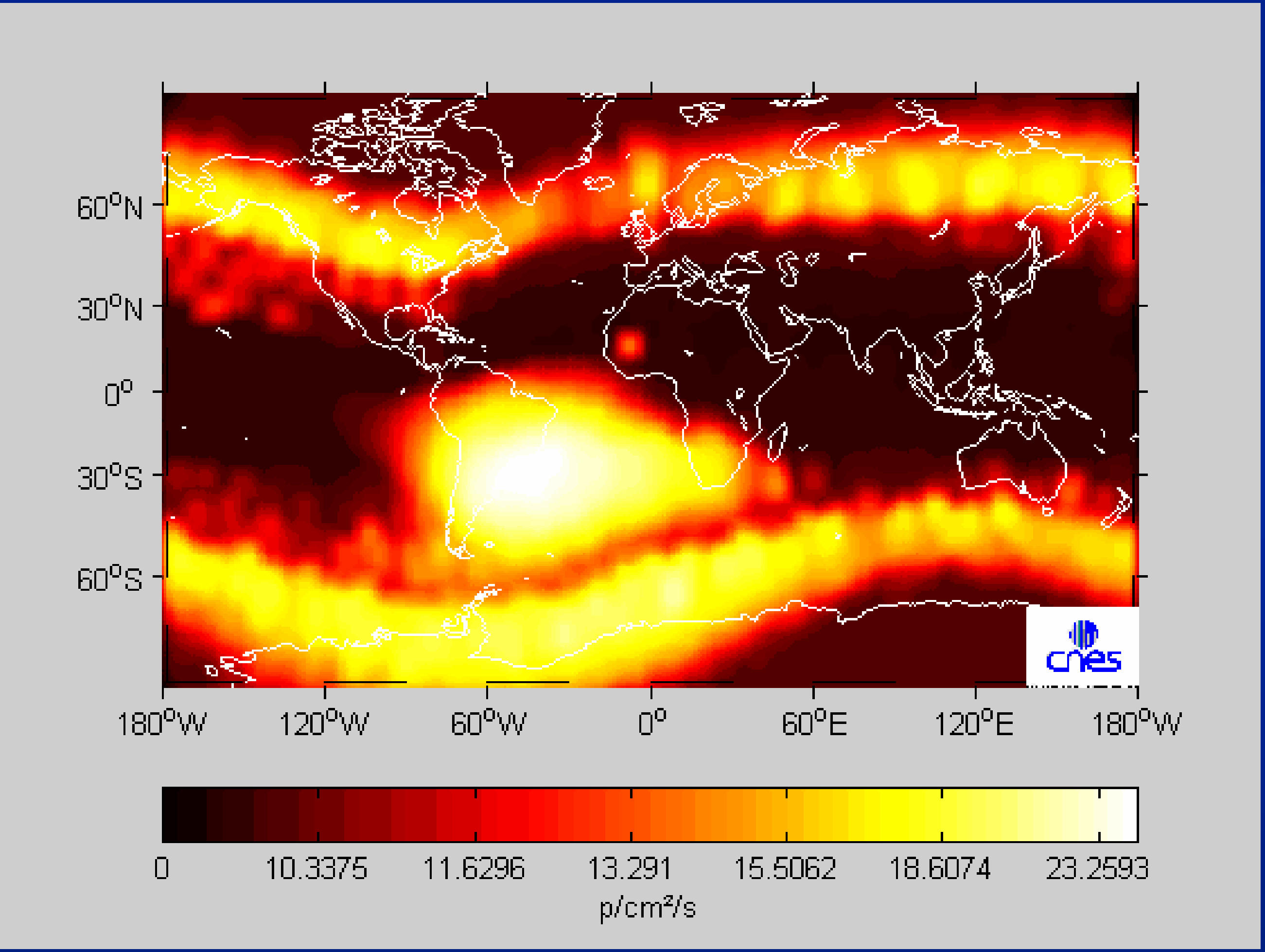


4-Day, 9-Orbit Averages

Daly, et al.

Electron Environment Dynamics

April 2001 Storm ~ 800 km



Radiation Effects

Radiation Effects on Space Systems

- Total Ionizing Dose – Degradation
  - Materials
  - Electronics
- Total Non-ionizing Dose – Degradation
  - Solar Cells
  - Detectors – e.g., CCDs, APS
  - Optocouplers
  - Optical lens
- Single Event Effects – Single particle strikes
  - Destructive – SEL, SEGR, SEB
  - Non-destructive – SEU, SET, SEFI, MBU
  - Loss of data to loss of mission
- Spacecraft Charging
  - Deep dielectric – Accumulation of charge on dielectrics with discharges on electronics – pulses and discharges
  - Surface – differential buildup - arcing, e.g. high voltage solar arrays

Technology Performance Predictions

Simulated conditions → Actual conditions

Environment Model

↓

Interaction Model → **Performance Prediction**

↑

Ground Test Data on Device

- **Accuracy of performance prediction is dependent on fidelity of ground test protocols and models.**
- **Design margins are used to accommodate uncertainties.**
  - Erodes capability
  - Can preclude use of newer technologies

Drivers for Component Selection

More demanding mission requirements

Short mission development times

Desire to operate in more severe environments

Commercial demand for electronics

Shrinking environment hardened market

Smaller, lighter spacecraft

Use of commercial off-the-shelf (COTS) components

Use of emerging technologies

Higher environment specifications

Projects have a choice of accepting risk or using older technologies.

Risk Management

- Understand consequences of effect
- Understand risk levels
  - Estimate risk of failure
  - Estimate loss of data collection/viewing time
- Design hardness into the system
  - Design circumvention/mitigation
  - Estimate overhead
  - Develop degradation plan
- Develop operational guidelines
  - Understand time profile of effect
  - Understand forecasting capability

Radiation Environment Specification

Janet's Top 10 Quotes About Environment Specification

10. "Just tell me yes or no."
9. "Don't you have a dose-depth curve laying around that I can use?"
8. "But the manufacturer told me that it is rad-hard."
7. "If it weren't space qualified, the manufacturer would not have sold it to me."
6. "Why on Earth would I want a person who 'provides radiation environment specifications' charging to my JON?"

Janet's Top 10 Quotes About Environment Specification

5. "I hired radiation specialists from ACME, and I need you to fix their calculations for my program review tomorrow."
4. "I called to get the radiation environment for my mission. I need the number now so I'll wait while you look it up in your table."
3. "Extra overhead like radiation engineering is not part of our program philosophy." (followed with 2 weeks of 3-page emails of questions about radiation)
2. "Well, my radiation plan was to add some spot shielding after the board is built."
1. "Hello, you don't know me but I'm launching next week and I need you to sign these waivers."

Why isn't there one number?

- Dependent on the effect
  - » Mechanism of the effect
  - » Intermittent vs. long term
  - » Each effect has an interaction model requiring different inputs
    - – Unshielded vs. shielded
    - – Differential vs. integral
- Dependent on mission phase
  - » Design – environment specification
  - » Mission planning – time distribution
  - » Risk analysis – statistics, confidence levels
  - » Operational guidelines – time distribution
  - » Anomaly resolution - nowcast
  - » Operations – forecast
- Environment is dynamic.
- Environment model development has not kept pace with technology changes.
  - » Models were designed for total dose applications
  - » Large design margins

How good are the environment models?

- Depends on the environment
  - Solar proton models are the best.
  - Trapped particle models are particularly bad – GEO.
  - Are for average or worst case conditions
  - Few have statistical distributions
- Environment is dynamic – the models are not.
- Environment model development has not kept pace with technology changes.
  - Models were designed for total dose applications
  - Large design margins

Characteristics of the Radiation Environment

- High energies
  - Electrons – 10s of MeV
  - Protons – 100s of MeV
  - Heavier Ions – 1000s of MeV
- Solar variability drives population levels
  - Long term solar cycle
  - Solar rotation
  - Solar storms, magnetospheric storms
- Magnetosphere filters galactic and solar particles
  - Polar, low-earth orbits are exposed to interplanetary levels during passes over the poles
- Trapped population has complex spatial distribution

Total Ionizing Dose (TID)

- Cumulative long term ionizing damage
- Strongly dependent on mission duration, orbit, and shielding
- Effects
  - » Threshold Shifts
  - » Leakage Current
  - » Timing Skew
  - » Functional Failures
- Can reduce with shielding
  - » Low energy protons
  - » Electrons

Total Ionizing Dose

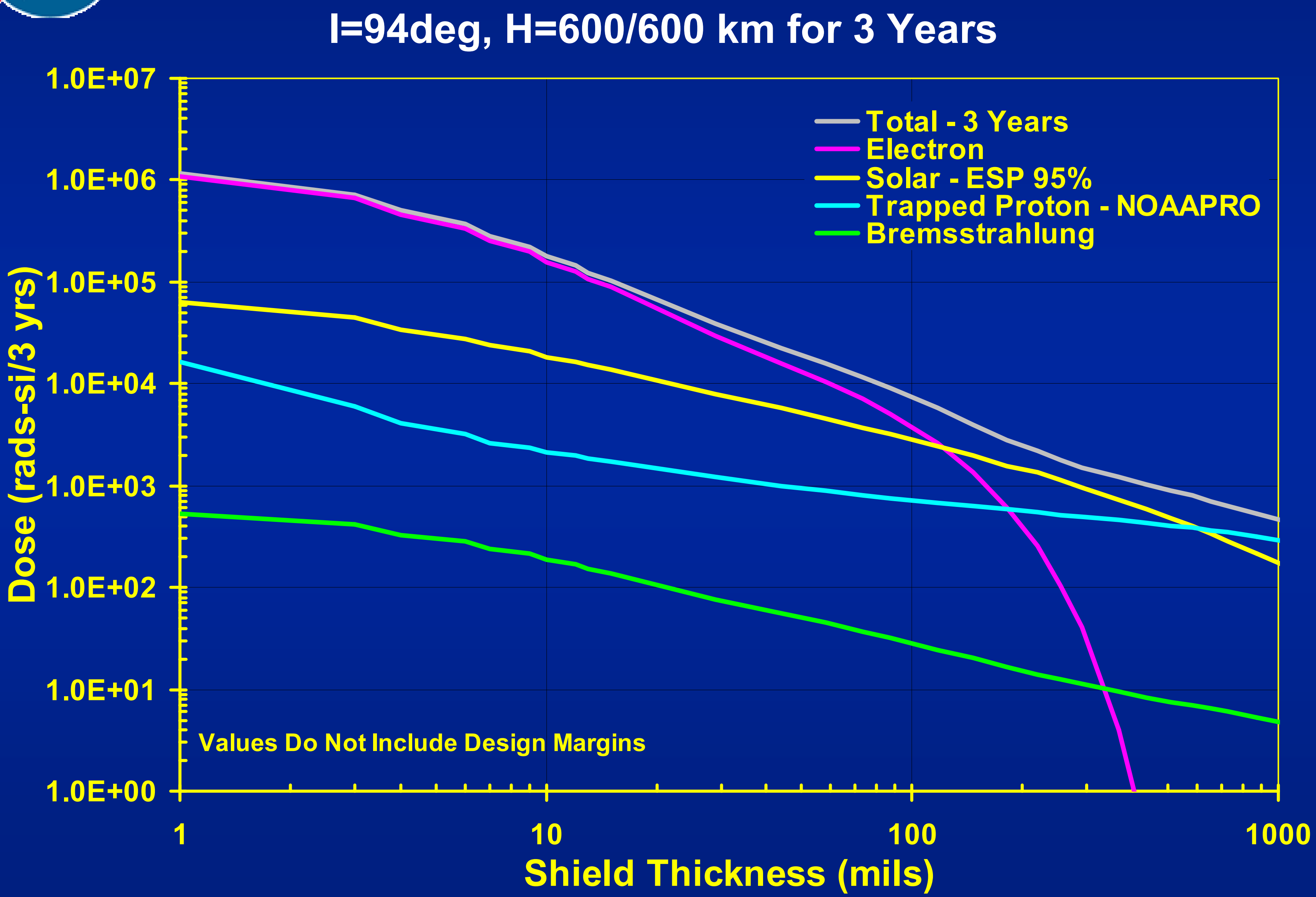
Contributing Particles

- Solar protons
- Trapped protons
- Trapped electrons
- Secondary
  - » Bremsstrahlung (high electron environments)

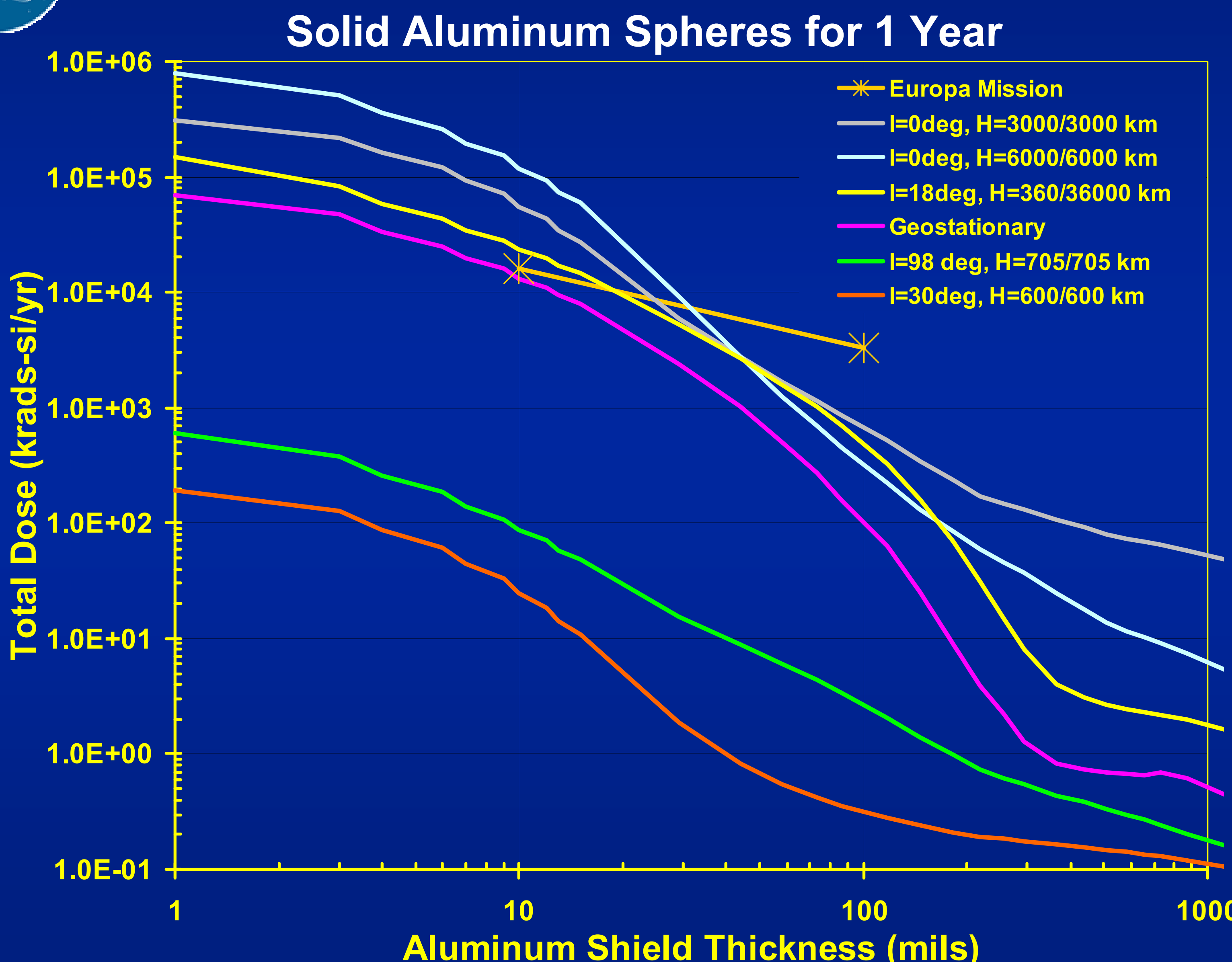
Environment Spec.

- Mission totals for end-of-life estimates
- Time profiles of accumulation for degradation planning
- Final specification
  - » Dose-depth curves
  - » Spacecraft specific dose levels

TID for Solid Spheres - GLAS



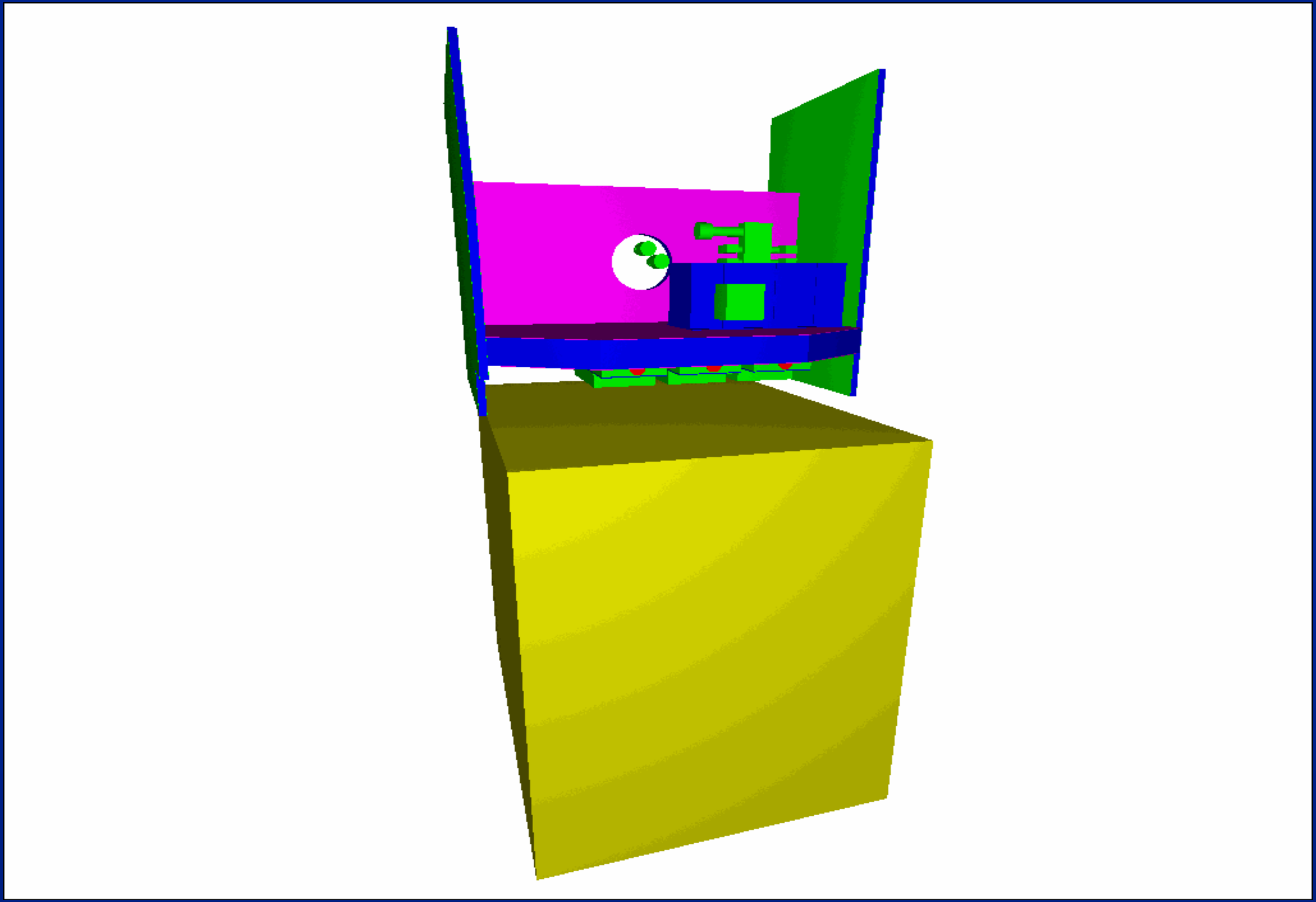
TID - Compare Missions



TID - System Hardening

- Risk avoidance
  - » Component selection
  - » Shielding strategies
    - – May need more accurate knowledge of component shielding
- Risk management
  - » Plan for graceful degradation
  - » Requires accurate knowledge of how device will respond in the space environment
    - – System criticality
    - – Application
    - – Characterization of device response
      - Parametric degradation
      - Enhanced low dose rate

GLAS Instrument: 3-D Radiation Model

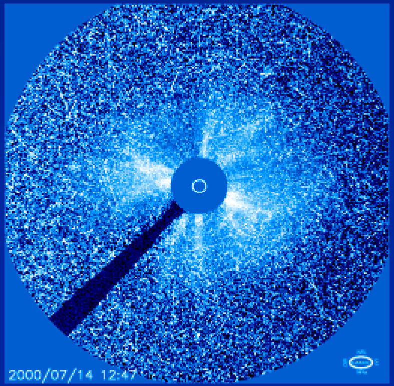


Location Specific Dose Data

Lidar Detectors						
3 yrs. - No Design Margin - See Robert Reed for Correct Design Margin						
Detector LI-1 (rads Si)		Detector LI-5 (rads Si)		Detector LI-9 (rads Si)		Detector LI-13 (rad
Trapped Protons	414	Trapped Protons	397	Trapped Protons	376	Trapped Protons
Trapped Electrons	469	Trapped Electrons	231	Trapped Electrons	194	Trapped Electrons
Solar Protons	993	Solar Protons	812	Solar Protons	699	Solar Protons
Brems.	6	Brems.	6	Brems.	7	Brems.
Total	1,882	Total	1,446	Total	1,276	Total
Detector LI-2 (rads Si)		Detector LI-6 (rads Si)		Detector LI-10 (rads Si)		Detector LI-14 (rad
Trapped Protons	389	Trapped Protons	399	Trapped Protons	397	Trapped Protons
Trapped Electrons	344	Trapped Electrons	295	Trapped Electrons	290	Trapped Electrons
Solar Protons	818	Solar Protons	831	Solar Protons	792	Solar Protons
Brems.	6	Brems.	8	Brems.	7	Brems.
Total	1,557	Total	1,533	Total	1,486	Total
Detector LI-3 (rads Si)		Detector LI-7 (rads Si)		Detector LI-11 (rads Si)		Detector LI-15 (rad
Trapped Protons	367	Trapped Protons	416	Trapped Protons	419	Trapped Protons
Trapped Electrons	263	Trapped Electrons	368	Trapped Electrons	399	Trapped Electrons
Solar Protons	714	Solar Protons	947	Solar Protons	960	Solar Protons
Brems.	5	Brems.	13	Brems.	7	Brems.
Total	1,349	Total	1,744	Total	1,785	Total
Detector LI-4 (rads Si)		Detector LI-8 (rads Si)		Detector LI-12 (rads Si)		Detector LI-16 (rad
Trapped Protons	359	Trapped Protons	435	Trapped Protons	456	Trapped Protons

Displacement Damage Dose (DDD)

- Cumulative long term non-ionizing damage
- Effect:
  - » Production of defects which results in charge transfer ratio (CTR) degradation
  - » Optocouplers, solar cells, CCDs, linear bipolar devices
- Shielding has some effect
  - » Solar cell cover glasses and mounting panels
  - » Only for some orbits



Displacement Damage Dose

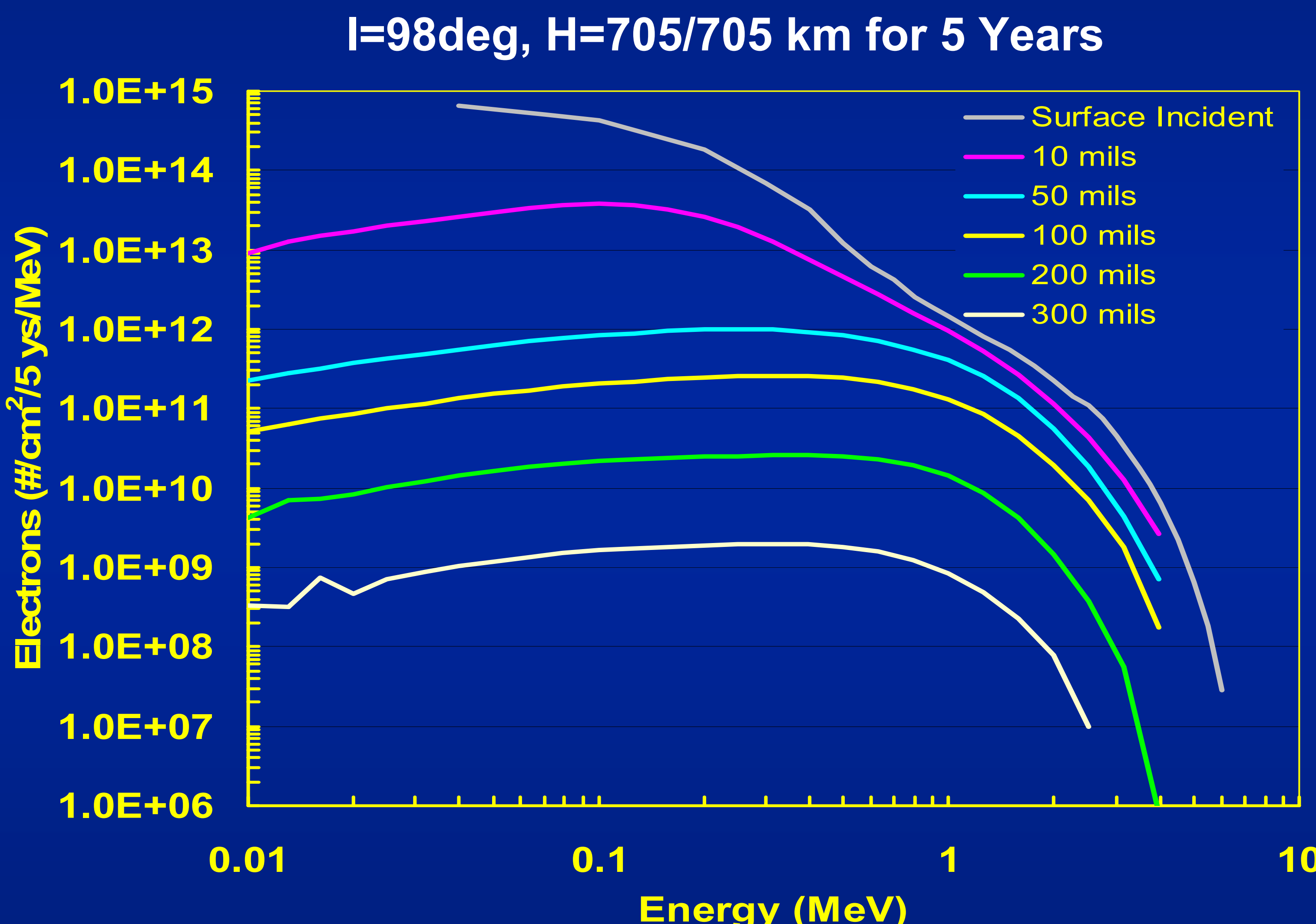
Contributing Particles

- Solar protons
- Trapped protons
- Trapped electrons
- Neutrons
  - Secondary from shielding
  - RTGs

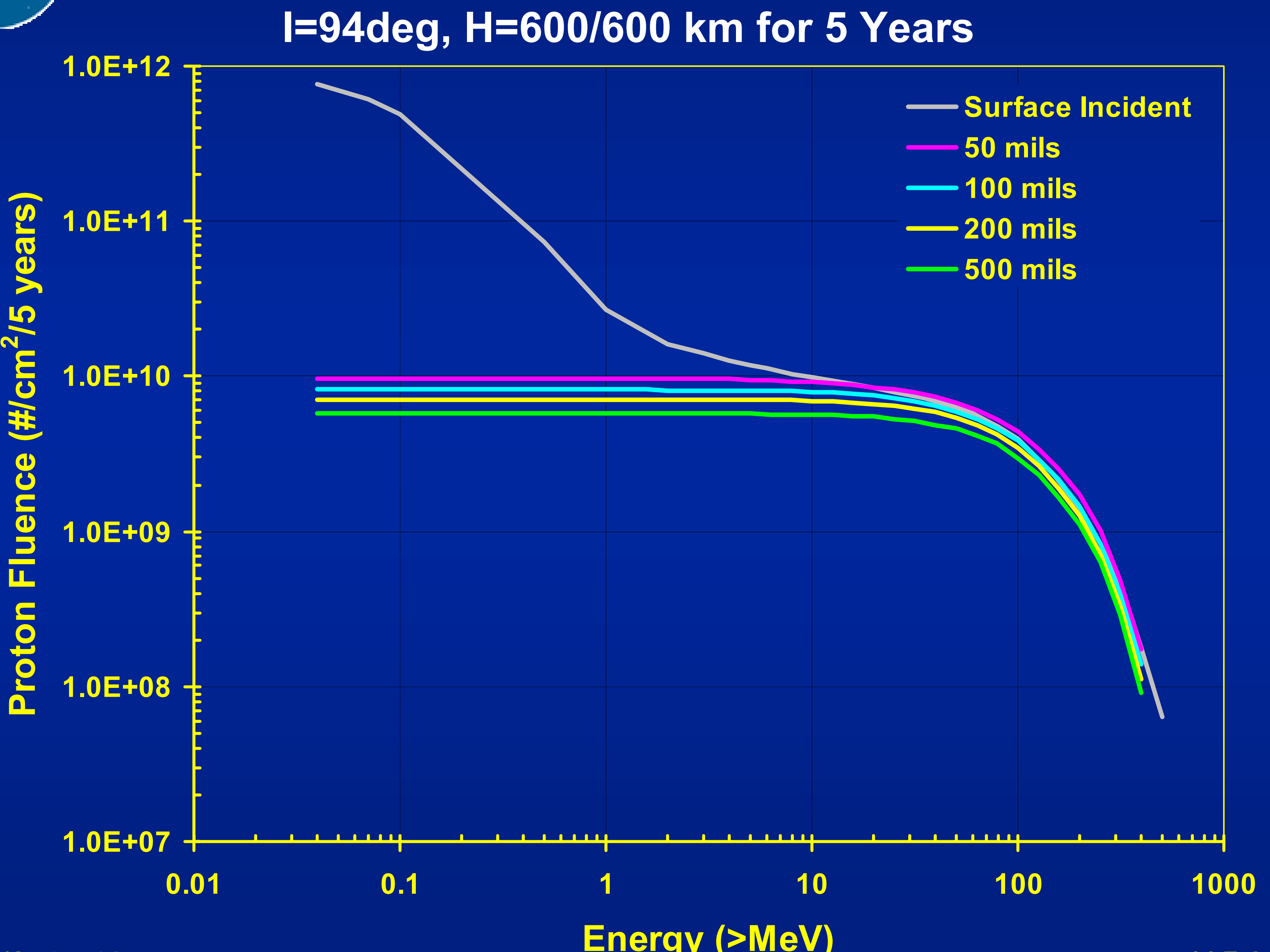
Environment Spec.

- Mission totals for end of life estimates
- Time profiles of accumulation for degradation planning
- Final specification
  - Energy spectra
  - Shielded

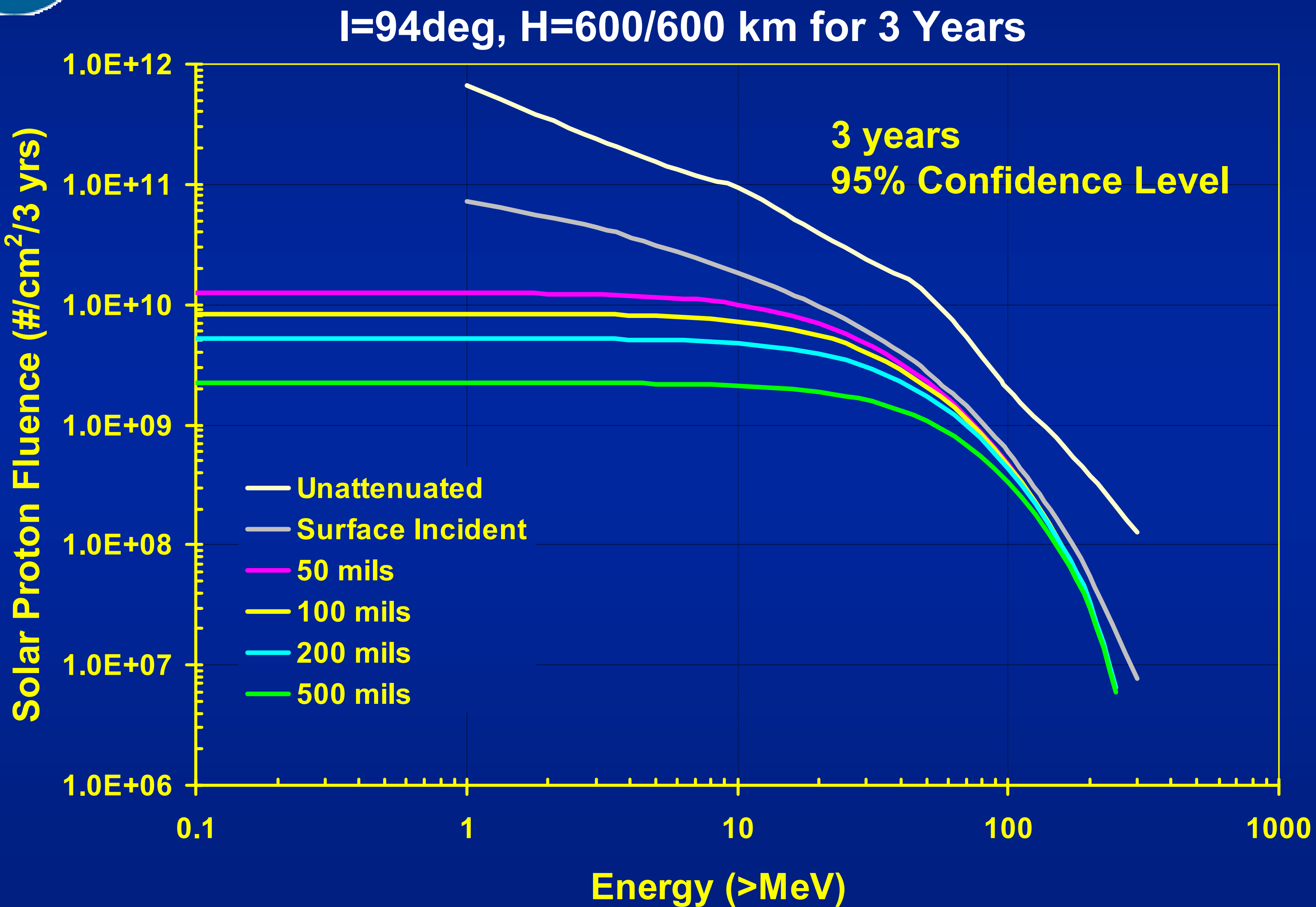
Trapped Electrons - EOS



Trapped Protons - GLAS



Solar Protons for DDD – GLAS

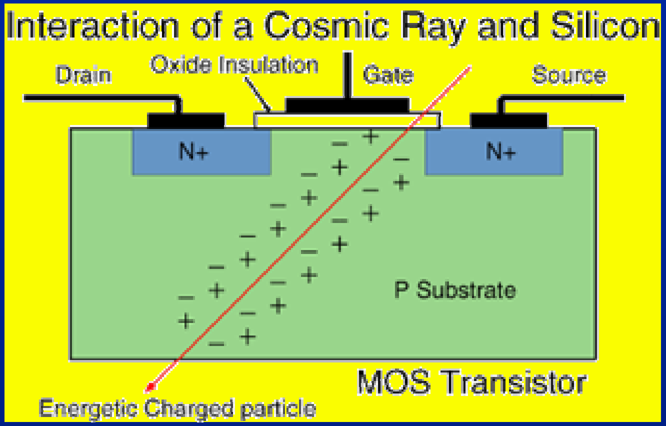


DDD - System Hardening

- Risk Avoidance
  - Not possible for all technologies
  - Protons are difficult to stop with shielding
  - Hardening techniques are not effective
  - Hardness changes with processing
- Risk Management
  - Reduce effect with shielding
  - Plan for degradation
  - Knowledge of radiation environment at detector
  - May require on-ground simulation
  - Models are not validated – need test flights
  - Mitigation through software

Single Event Effects

- Event caused by a single charged particle
- Effects:
  - » Non-destructive: SEU, SET, MBU, SEFI, SHE
  - » Destructive: SEL, SEGR, SEB
- Severity is dependent on:
  - » type of effect
  - » system criticality
- Shielding has little effect



Single Event Effects (SEEs)

Contributing Particles

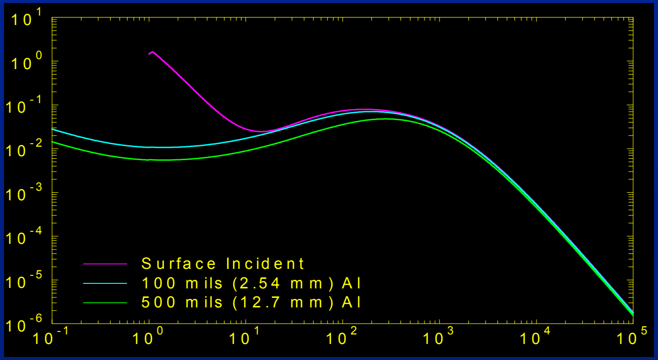
- Heavy ions – direct ionization
  - Galactic cosmic ray
  - Solar
- Protons – indirect ionization (mostly)
  - Trapped
  - Solar

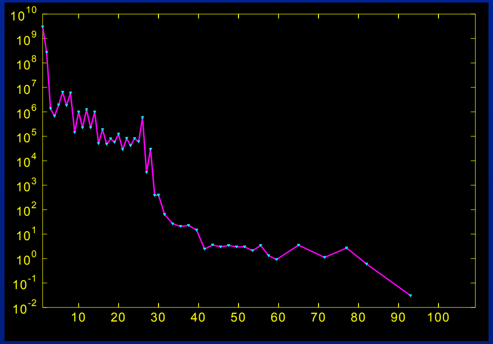
Environment Spec.

- Time profiles
- Peak levels
- Background levels
- Final specification
  - Heavy ions - linear energy transfer (LET)
  - Protons - energy spectra

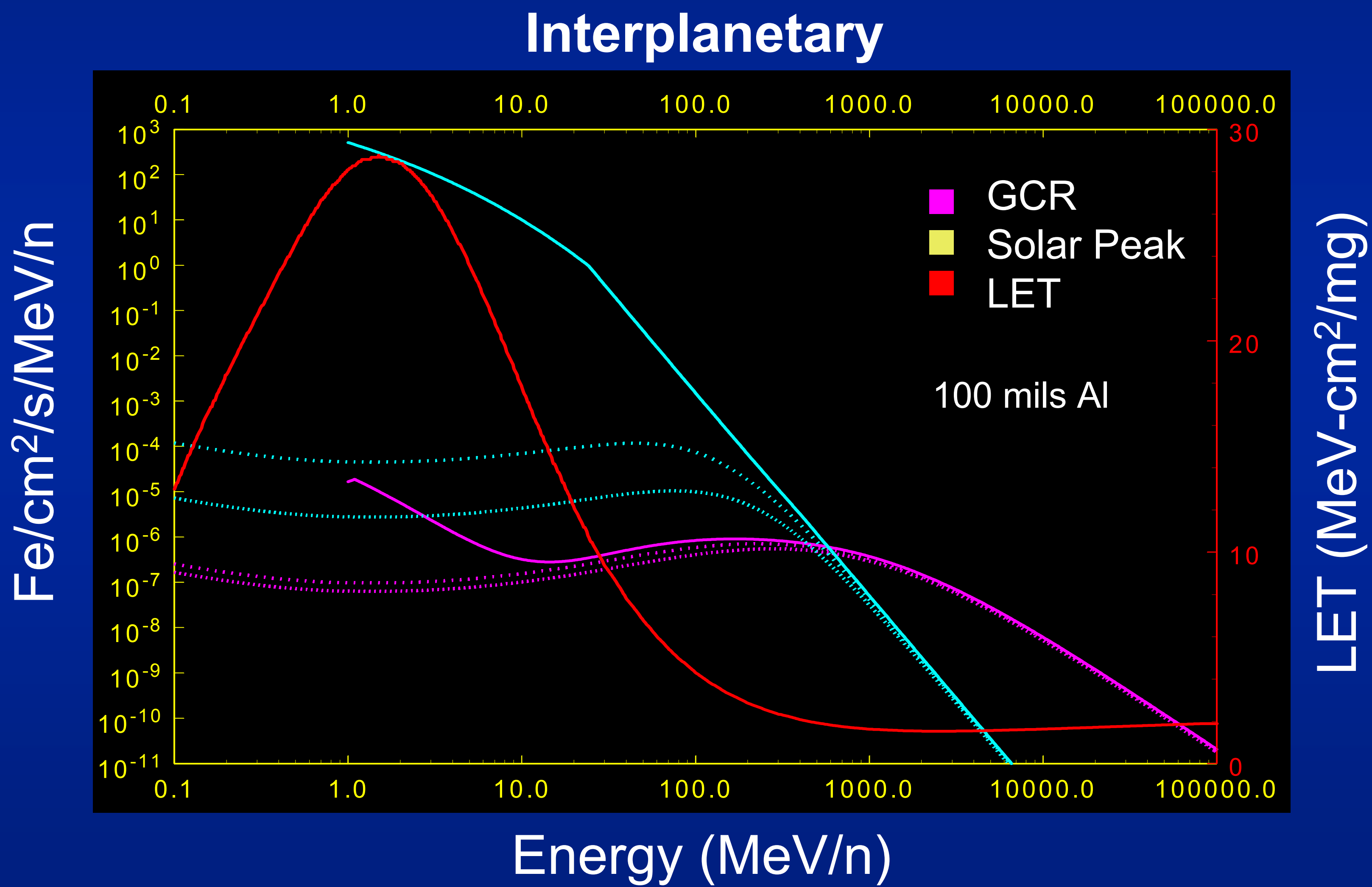
Heavy Ions - The "LET" Metric

- Particle passing through sensitive node creates an ionization path - direct ionization
- Need to characterize the effect of all heavy ions
  - » All energies
  - » All elements
- Linear Energy Transfer (LET) metric is used
  - » Energy loss per unit path length (de/dx)
  - » Units are MeV/cm
  - » Divide by density of material to get MeV-cm²/mg
- Defines complex environment with one profile



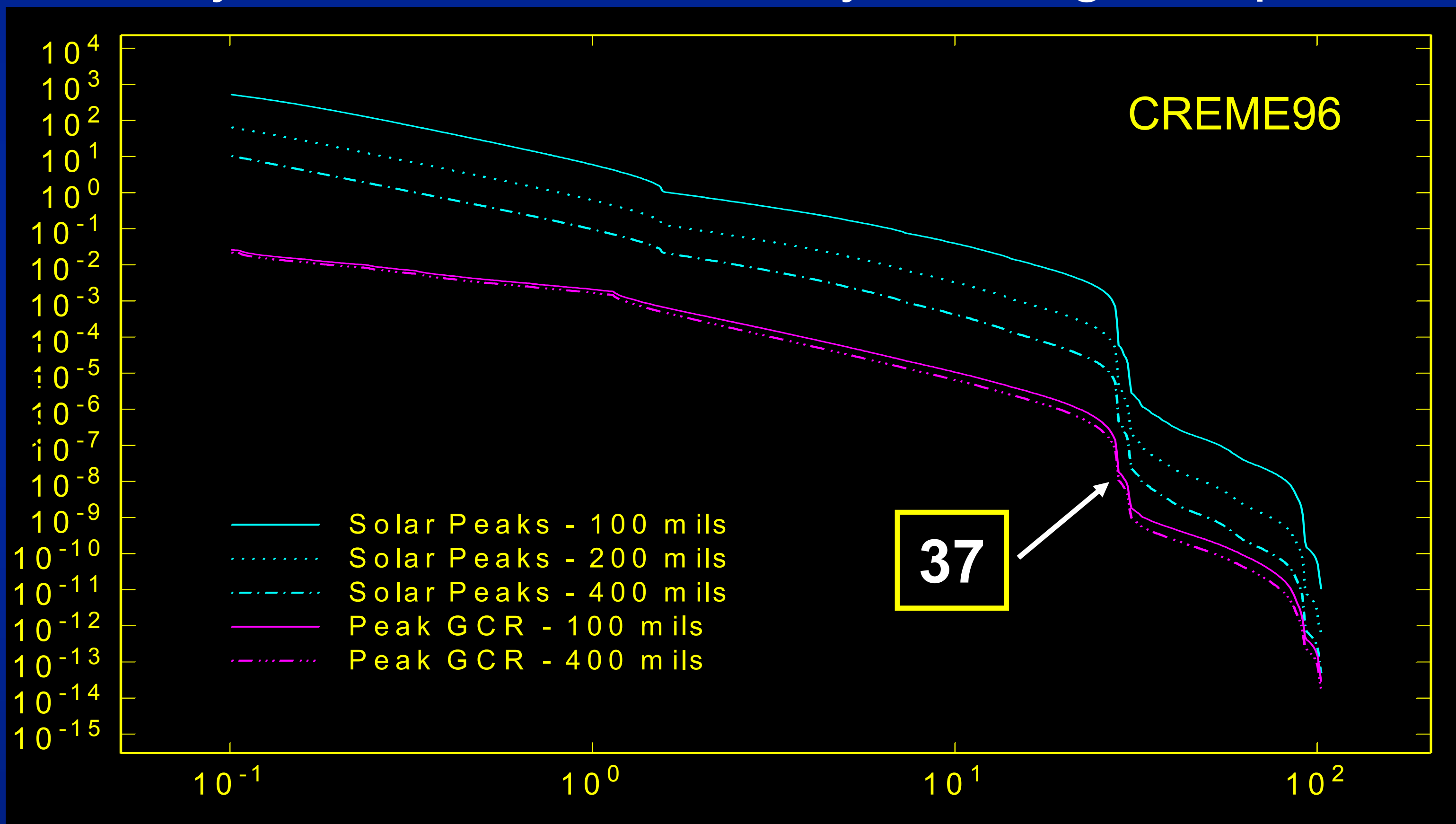


The LET Metric for Fe



Heavy Ions for SEEs ~ GEO

Heavy Ions - Unattenuated by the Magnetosphere

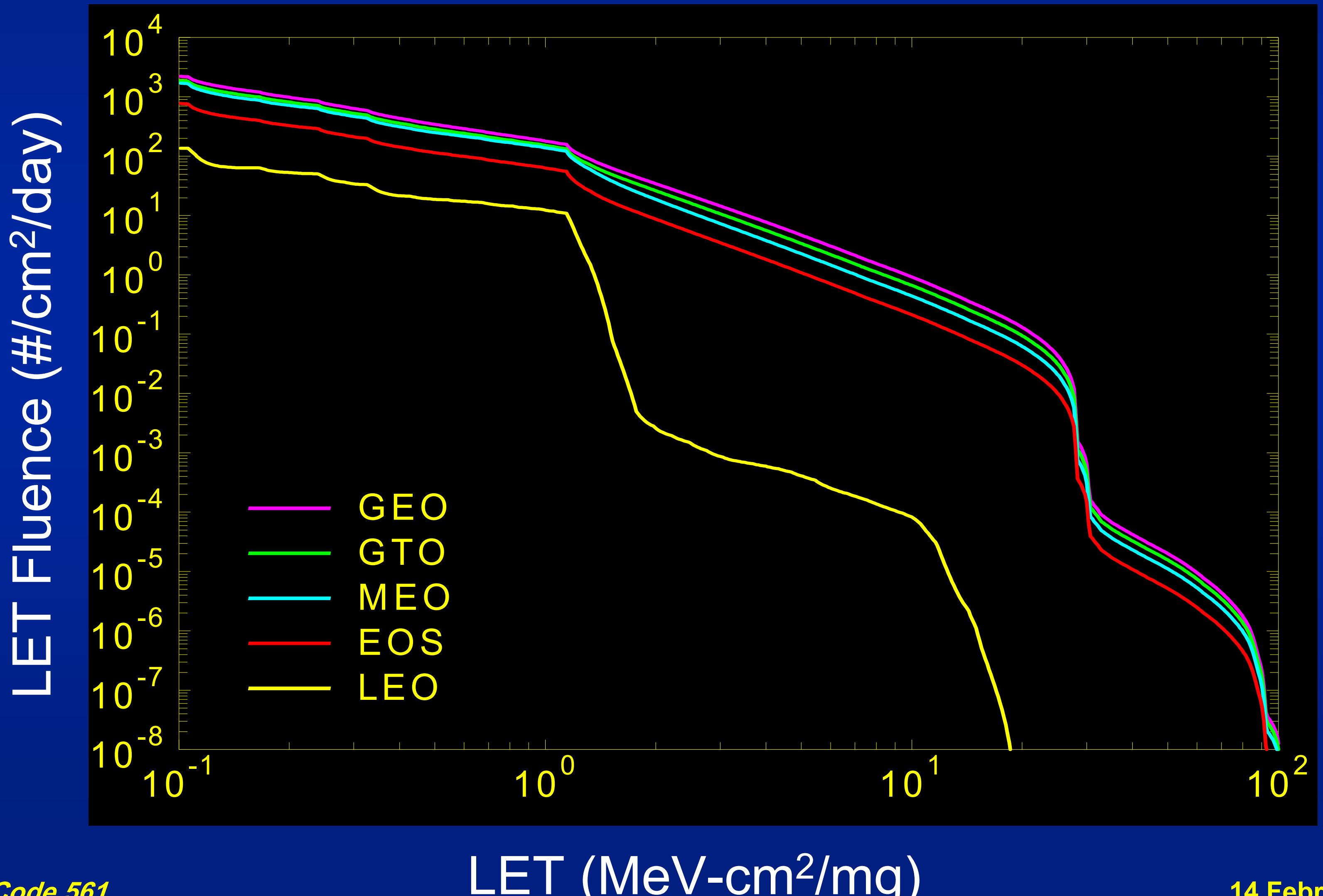


Fluence ($\#/cm^2/s$)

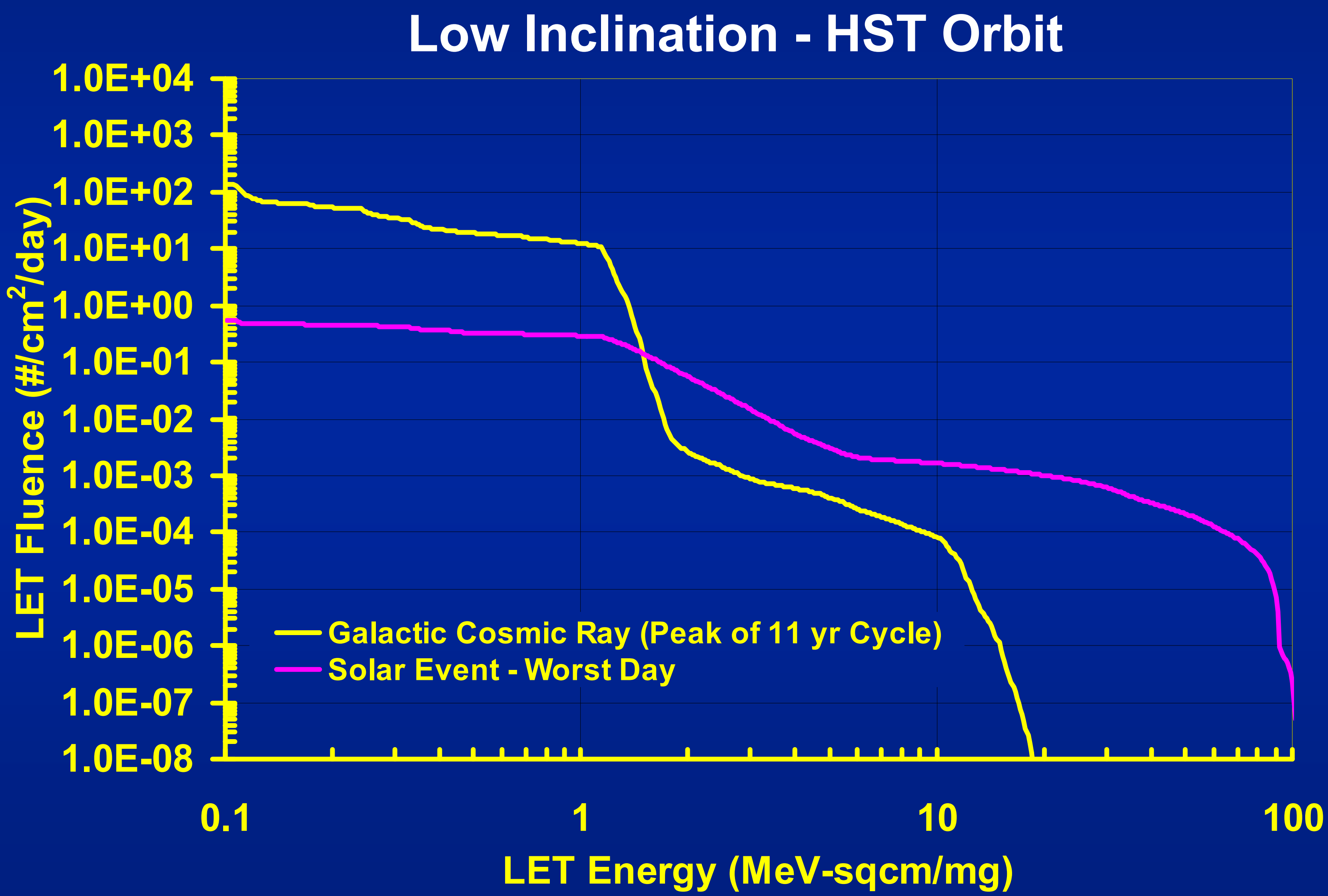
LET ($MeV\text{-}cm^2/mg$)

LET Dependence on Orbit for GCRs

100 mils Aluminum Shielding

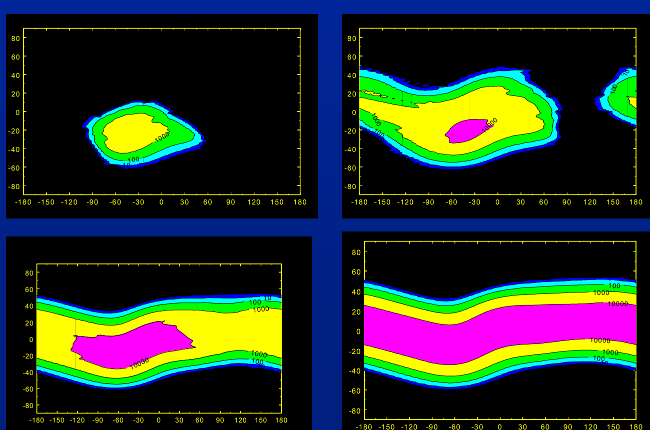


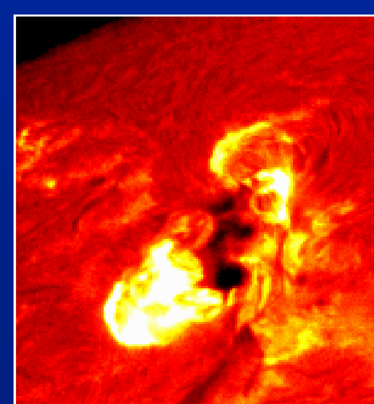
Dependence on Solar Activity

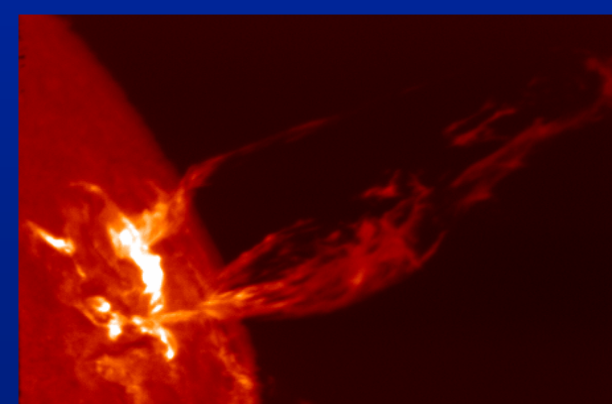


Protons - The “Particle Energy” Metric

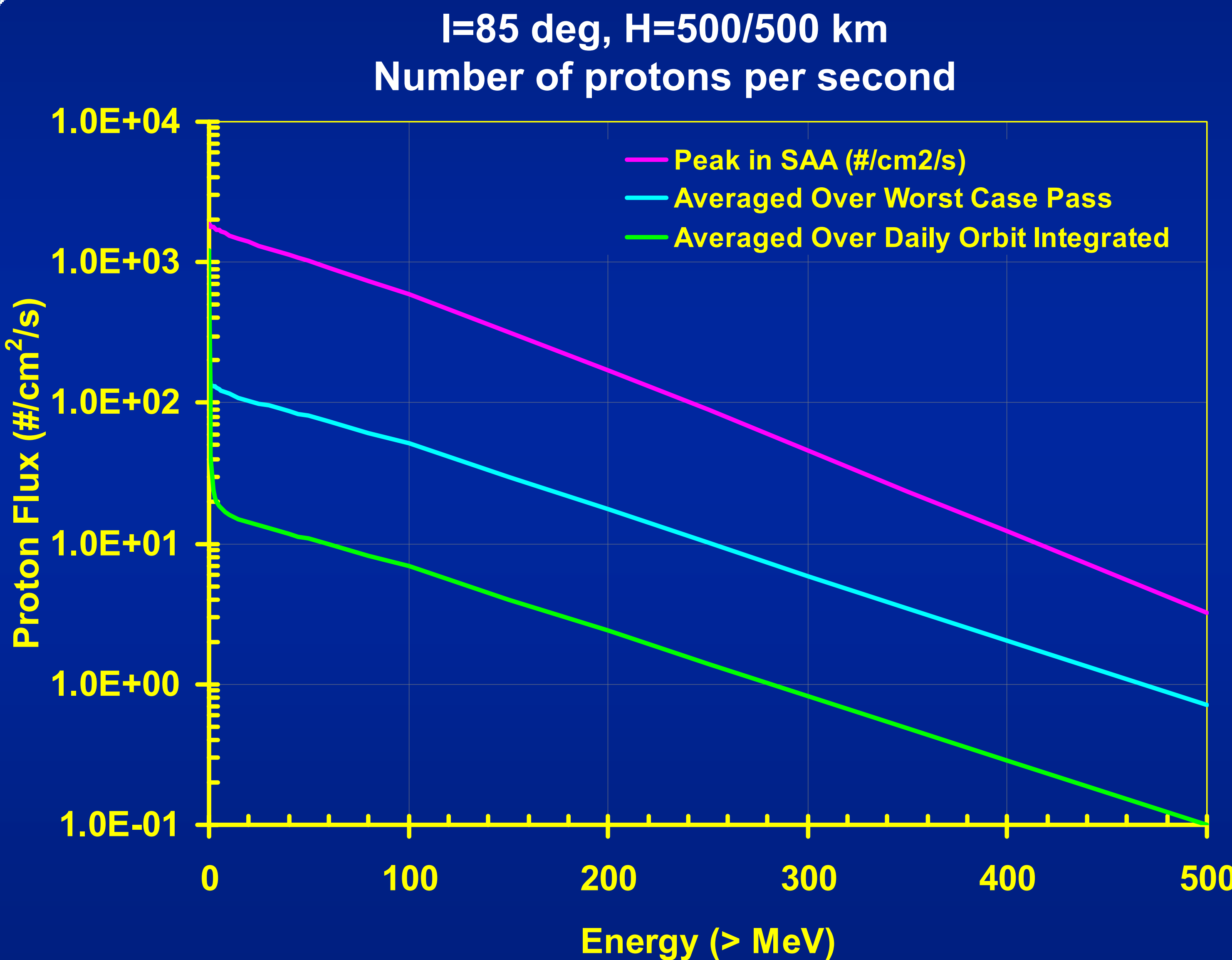
- Indirect ionization
  - » Proton hits nucleus in the materials near a sensitive node.
  - » Heavy ion is created.
  - » Heavy ions with sufficient range create ionization.
- Codes account for heavy ion production
- Energy of incident particle is more important
- Direct ionization by protons?
  - » Rate increased by 10^5



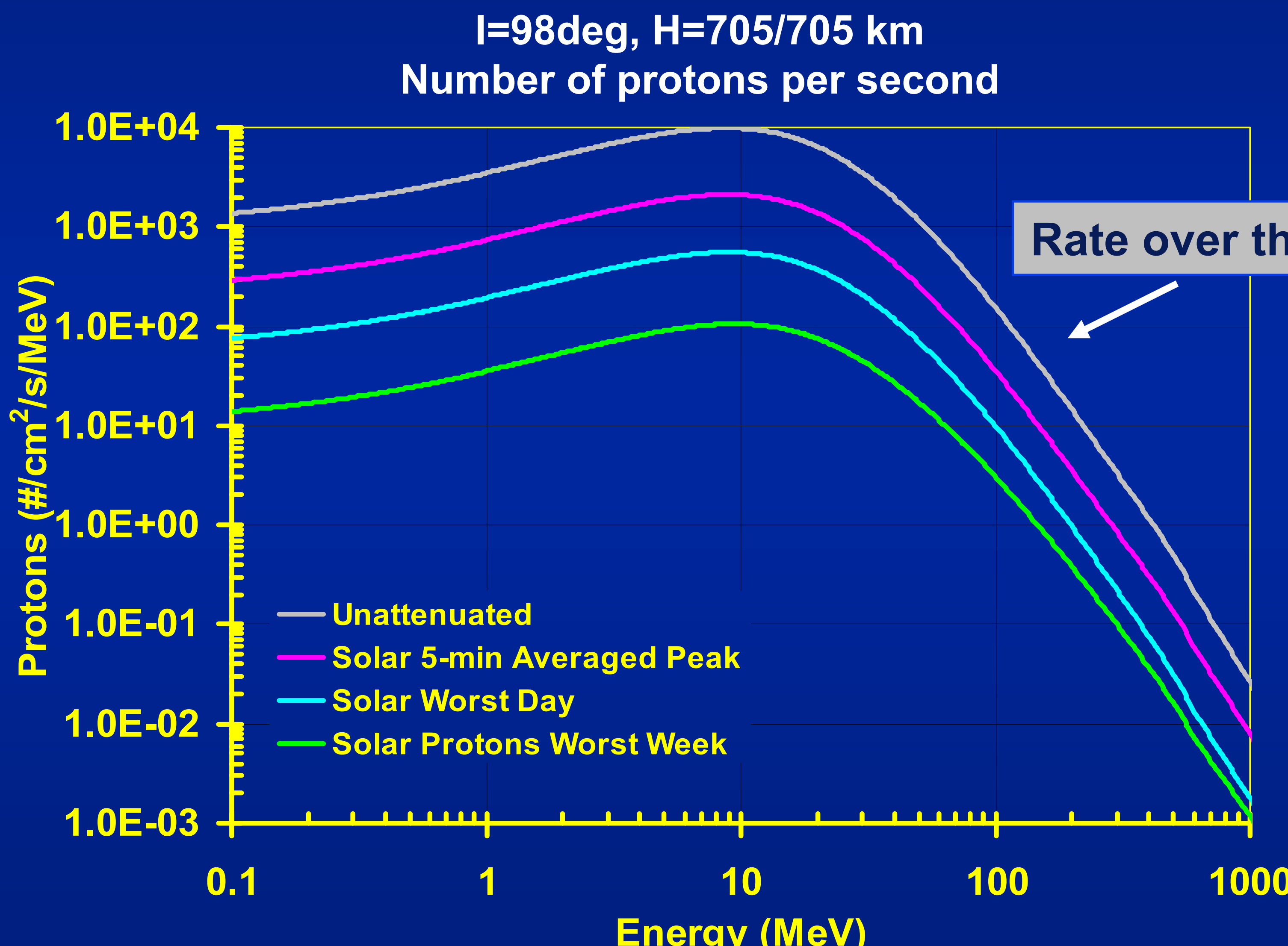




Trapped Protons for SEEs - GRACE



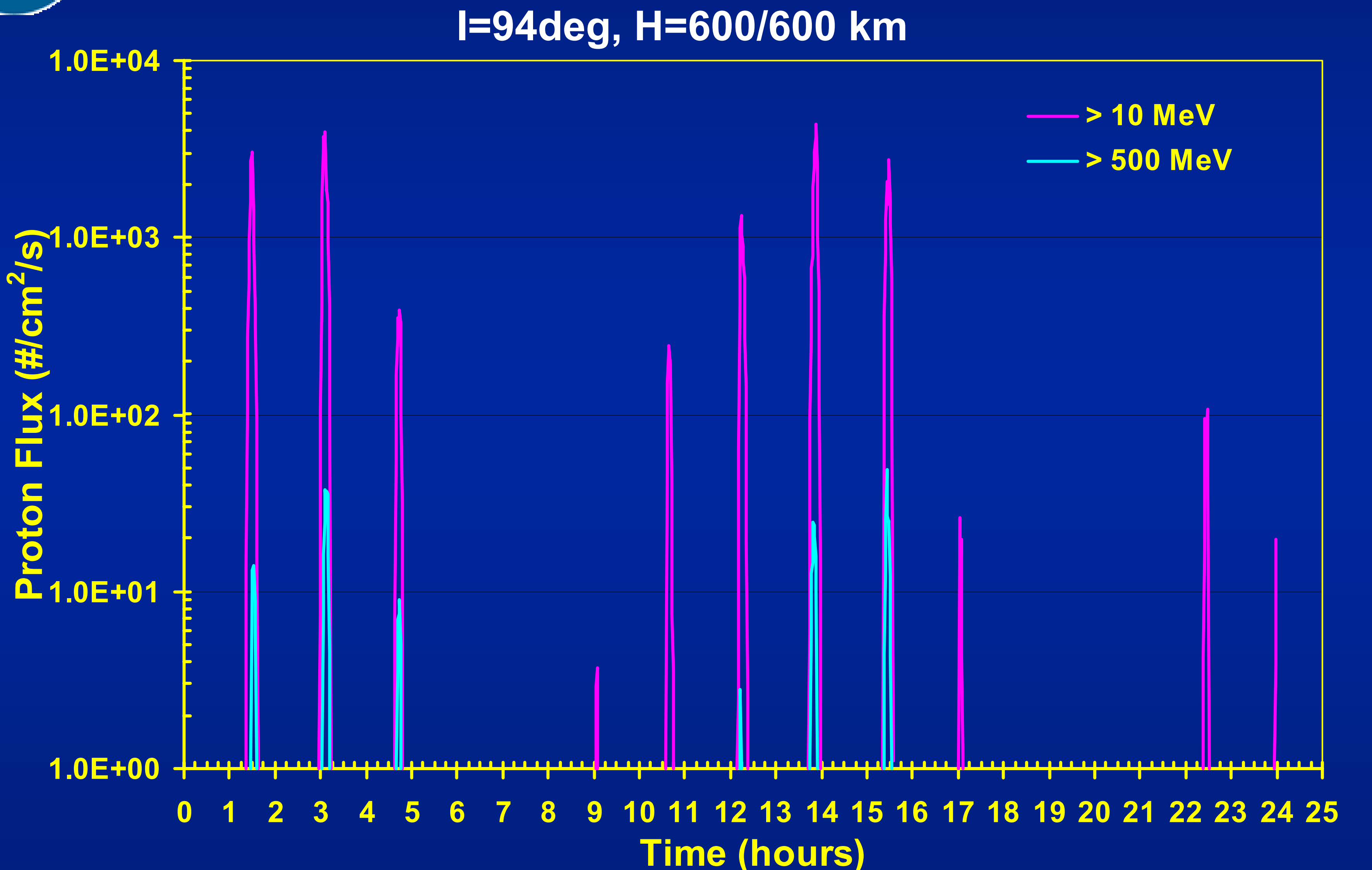
Solar Protons for SEEs - TERRA



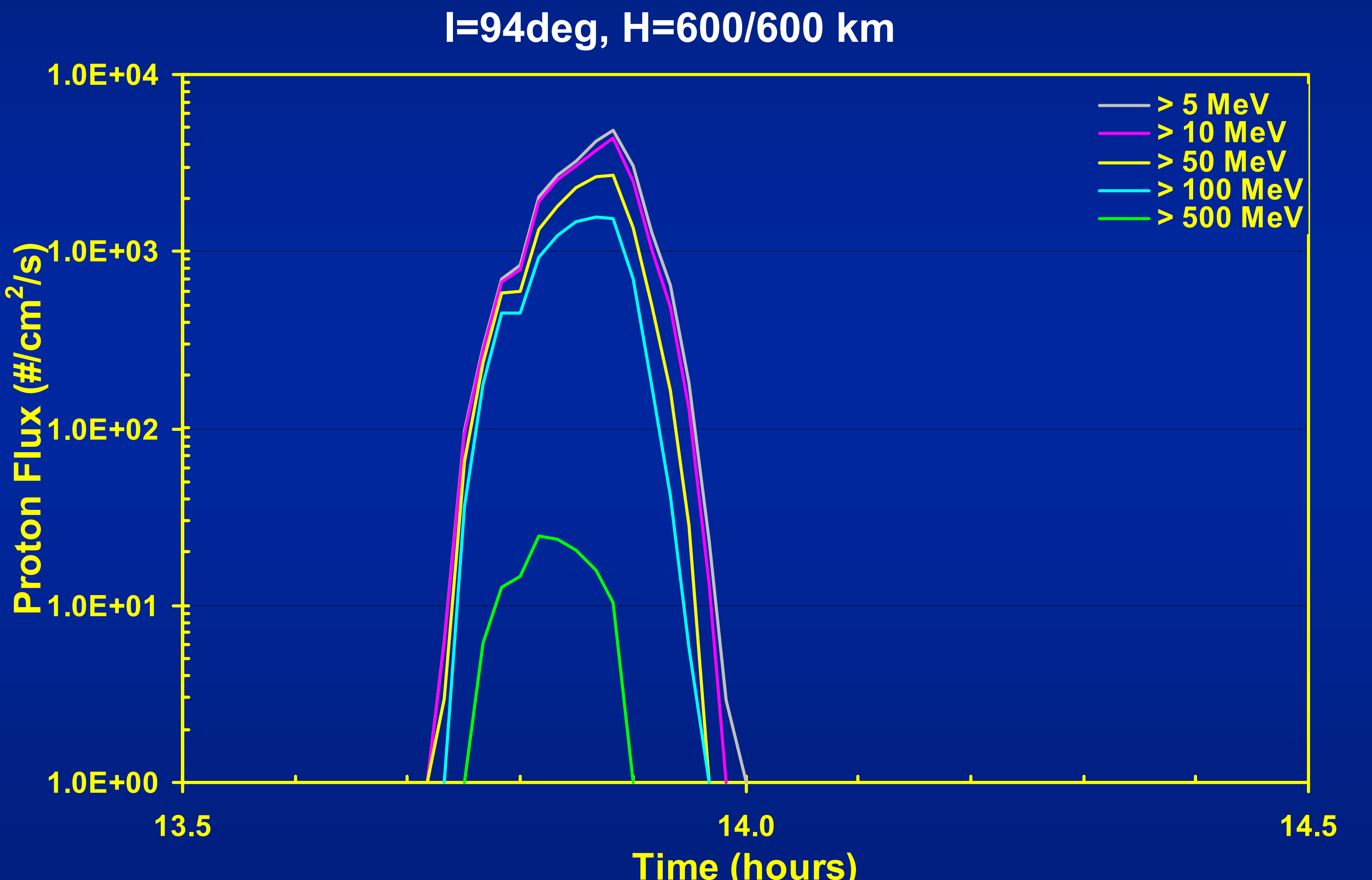
System Hardening for SEEs

- Risk avoidance
  - » Rad-hard does not always imply SEE hard.
  - » Shielding is not an effective mitigator.
  - » System should be hard to latchup.
    - – Is not always possible to find replacement part
  - » Performance requirements push designers to use sensitive technologies.
- *Risk management*
  - » Typical for non-destructive events - EDAC
  - » Destructive - rate prediction for assessment of level of risk
  - » Both require accurate knowledge of how device will respond in the space environment
    - – Type of effect & system criticality
    - – Definition of peak & average environments
    - – Characterization of device response to particle hits

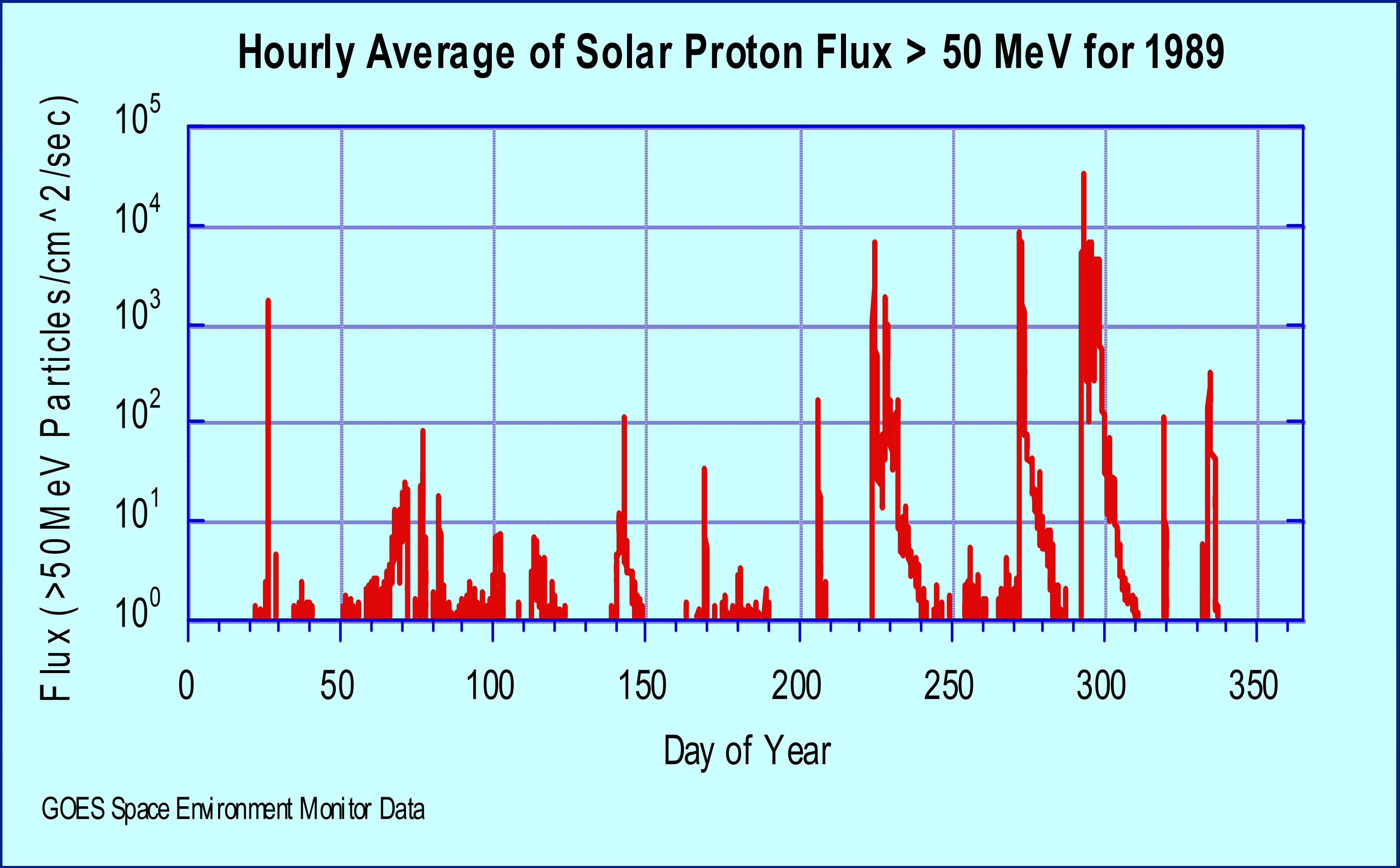
Trapped Protons - SAA Passes



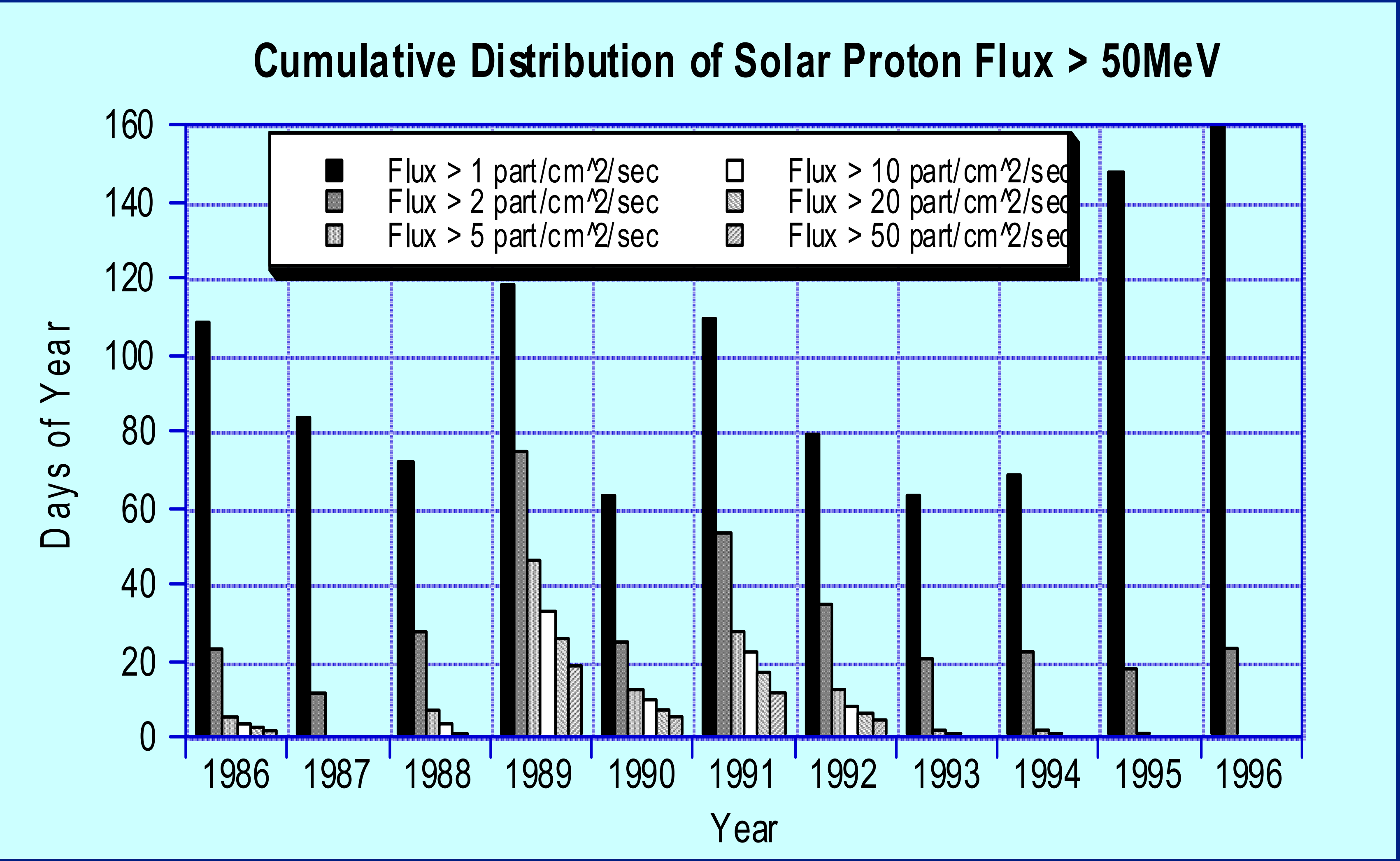
Worst Case SAA Pass - Protons



Time Profiles – Mission Planning



Time Profiles – Mission Planning

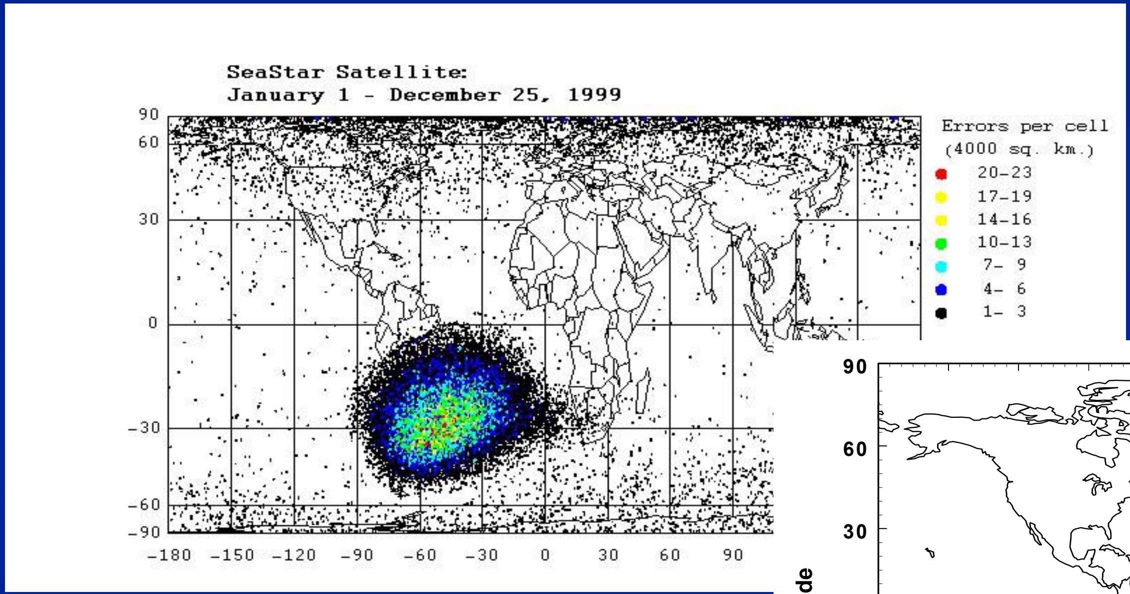


Single Event Effects on Missions

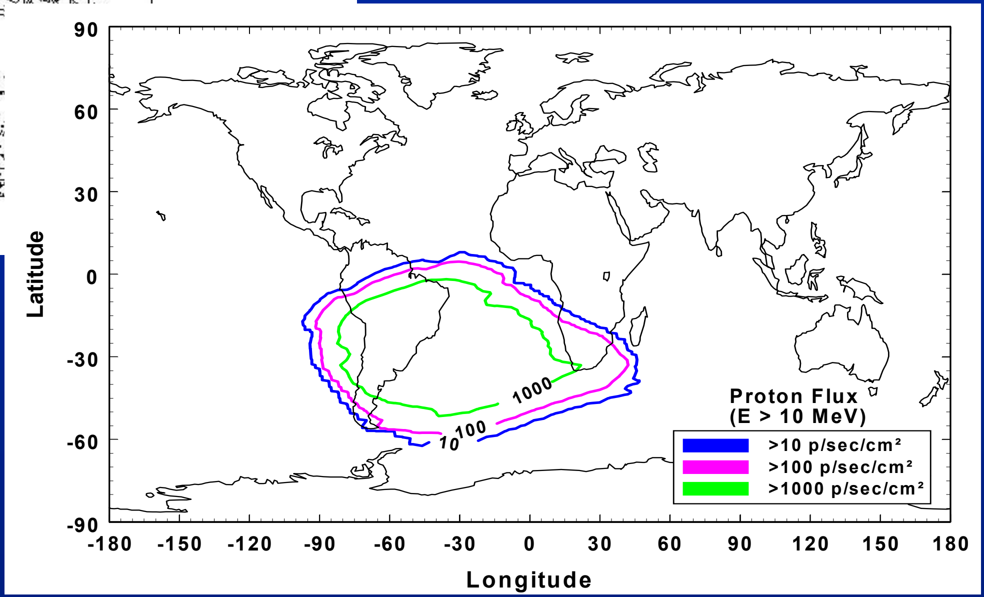
- MAP – Single event transient on a voltage comparator
- HST – Single event transients on an optocoupler
- Terra – Single particle events on the solid state star tracker (SSST)
- Flight Data Recorders – Single event upsets
  - HST
  - SAMPEX
  - Seastar

Seastar - Single Event Upsets

Single Event Upsets on Flight Data Recorder
January 1 - December 25, 1999 – 705 km

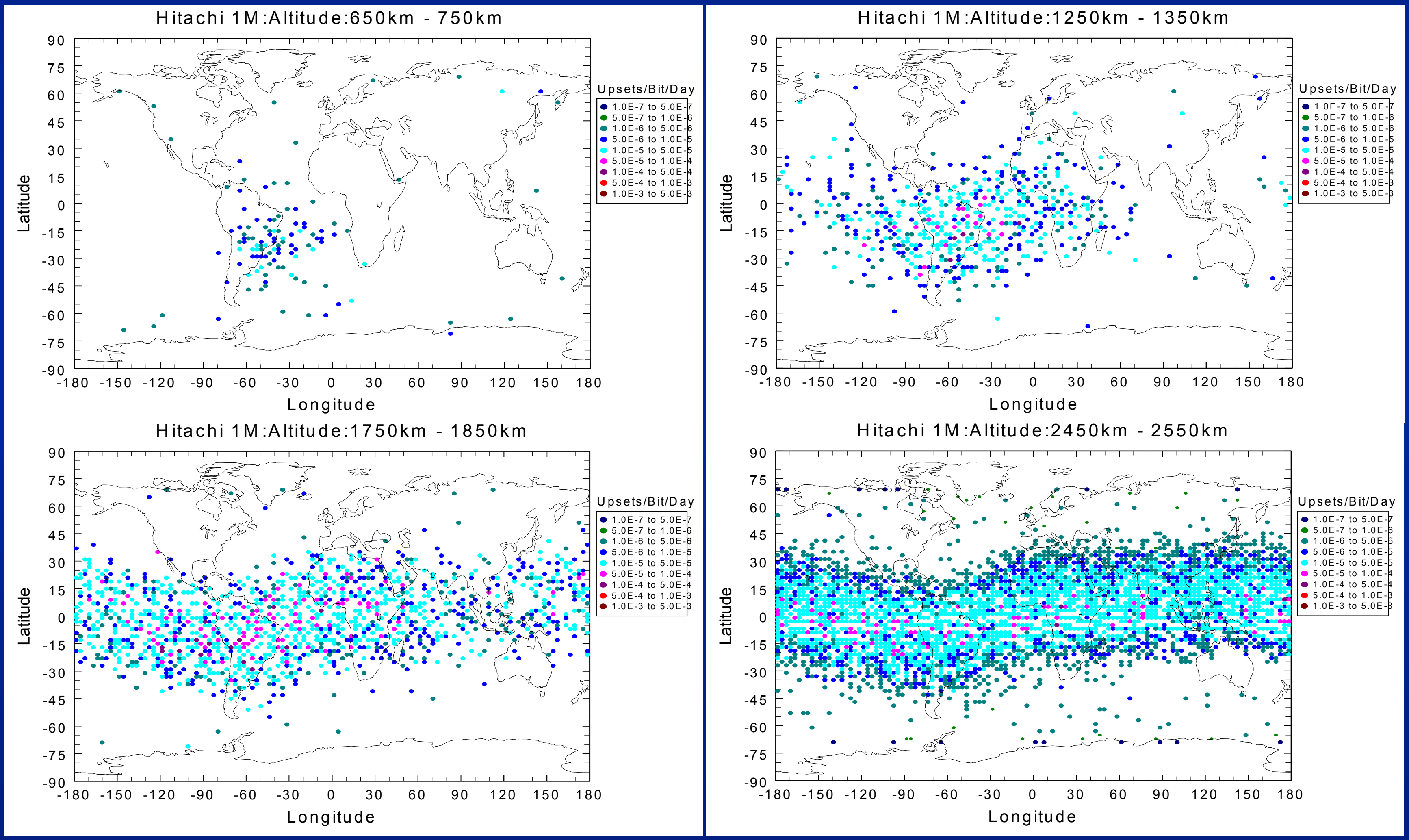


COTS DRAM Technology



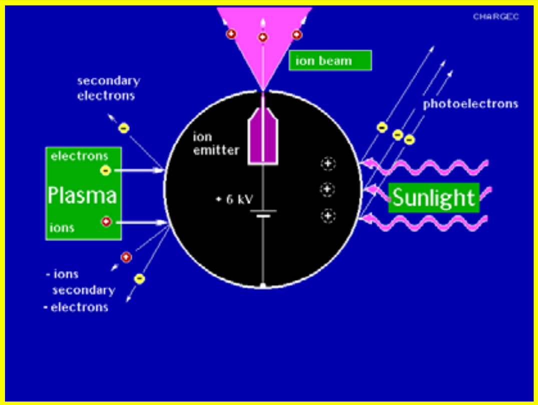
No science data lost

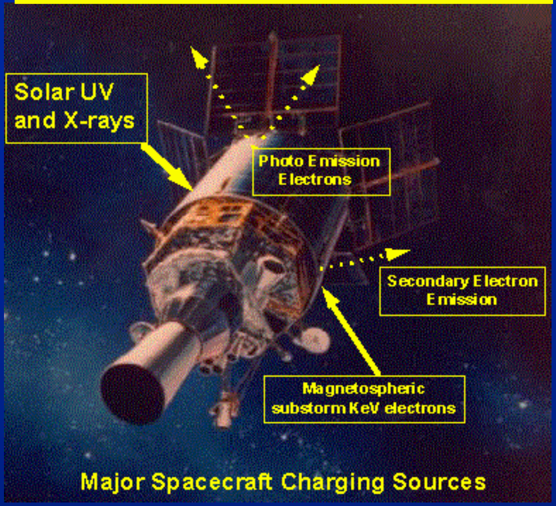
SRAM Upset Rates on CRUX/APEX



Spacecraft Charging/Discharging

- Two types
  - » Surface charging
  - » Deep dielectric charging
- Different sources and design mitigation techniques
- Effects of discharge arcing
  - » Background interference on instruments & detectors
  - » Biasing of instrument readings
  - » Physical damage to materials
  - » Arcing – upsets to electronics, increased current collection, reattractition of contaminants, ion sputtering which leads to acceleration of erosion of materials





Major Spacecraft Charging Sources

Surface Charging

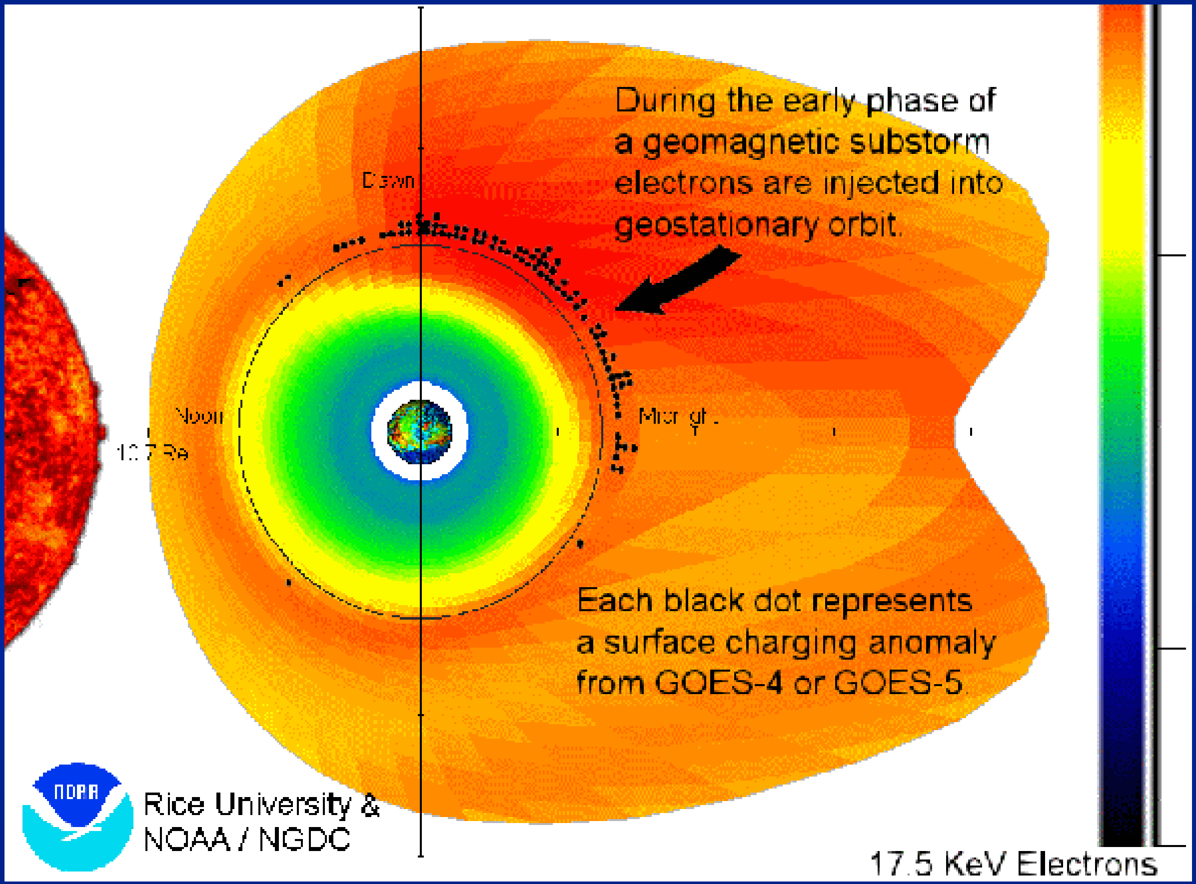
- Induced charge on surface
  - Low energy plasma & photoelectric currents
  - “Hot” plasma (LEO vs. GEO)
- Orbits with high risk
  - LEO – maybe
  - MEO - ? probably
  - GEO - generally a greater concern
  - GTO
- Risk factors
  - Geomagnetic substorms resulting in injection of keV electrons
  - Passage from eclipse to sunlight – positive charge surface due to photoelectron emission
  - Large spacecraft
  - High voltage power system

Deep Dielectric Charging

- Process
  - High energy electrons penetrate into dielectric materials (circuit boards and cables).
  - Charge builds up and gives rise to intense electric fields.
  - When charge exceeds the breakdown potential, discharge occurs.
- Missions affected
  - Any spacecraft spending long periods in Van Allen belt electron regions
  - MEO, GEO, GTO, Phasing loops
  - Jovian
- Risk factors
  - Accumulation of $> 10^{10}$ E > 1 MeV electrons within 10 hours
  - Accumulation of $> 3 \times 10^{8}$ E > 2 MeV electrons/day for 3 consecutive days
  - Accumulation of $> 10^{9}$ E > 2 MeV electrons in a single day

Charging in GEO

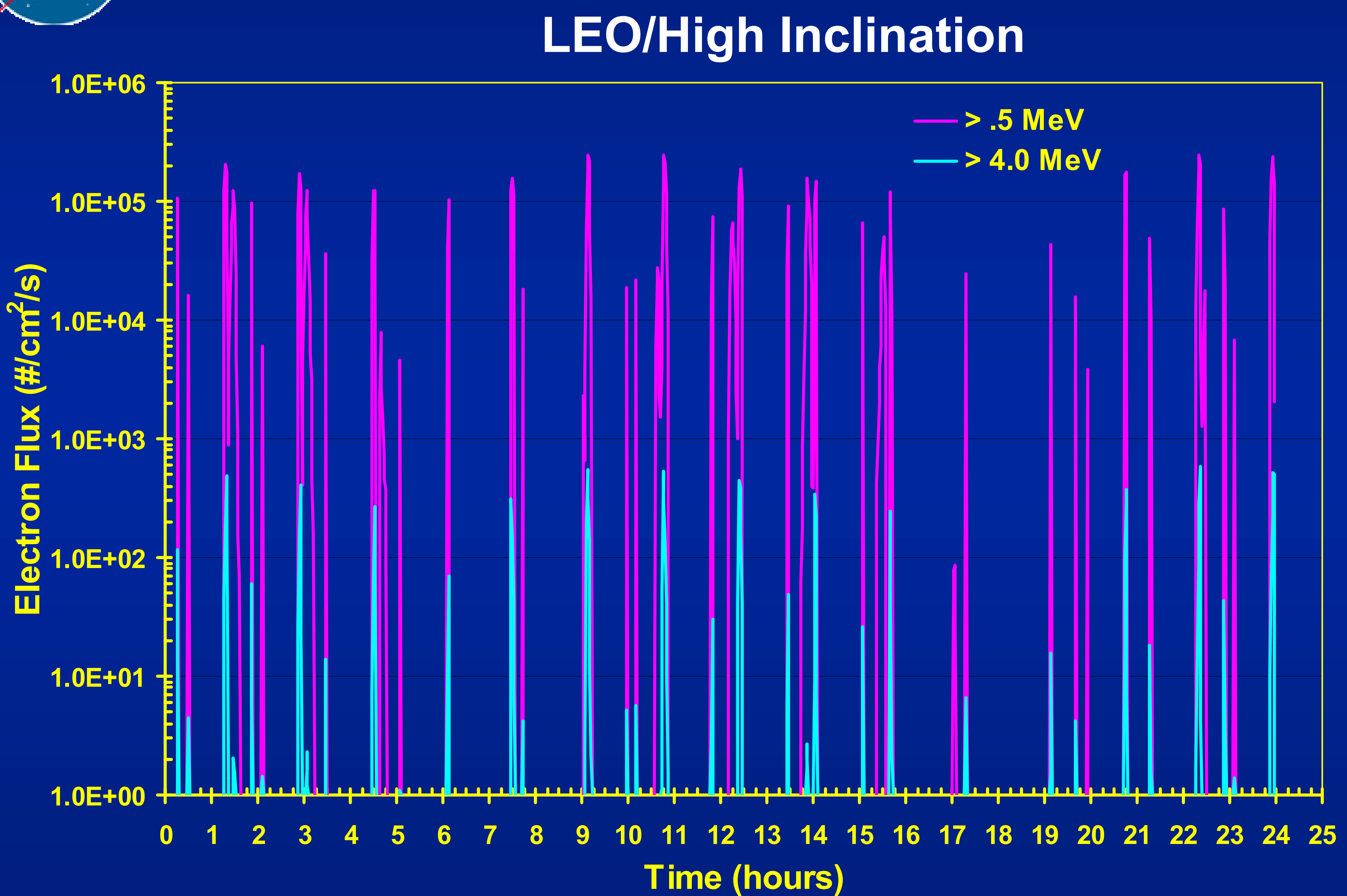
- Strong local time effects
- Solar storm effects
- Experience base is in LEO & GEO



Spacecraft Charging

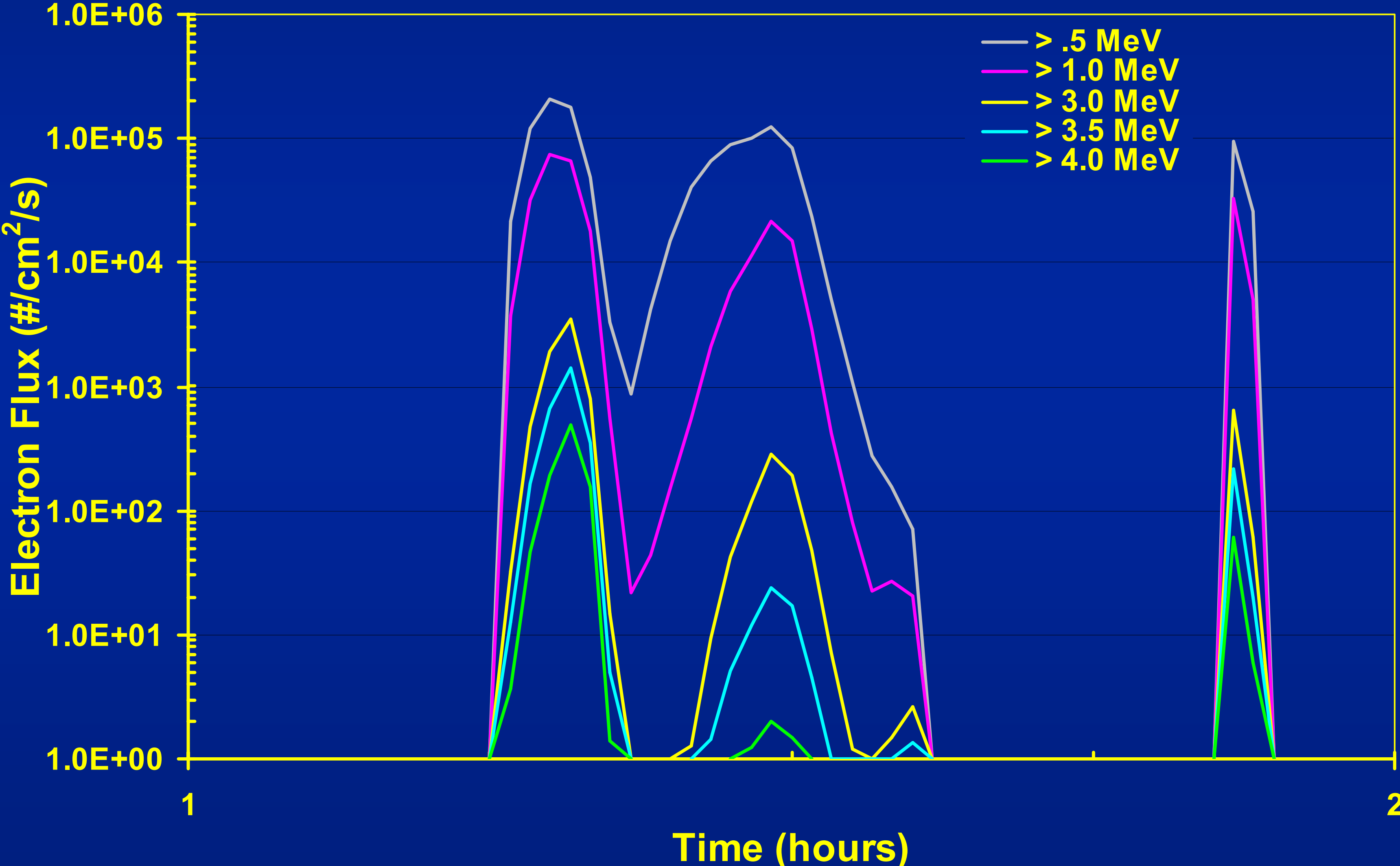
Contributing Particles	Environment Spec.
□ Surface » Plasma □ Deep dielectric » High energy electrons » > 1 MeV » > 2 MeV	□ Accumulation time □ Total accumulations □ Space weather conditions □ Final specification » Plasma levels » Electron energy spectra » Accumulation profiles

Trapped Electrons - SAA Passes

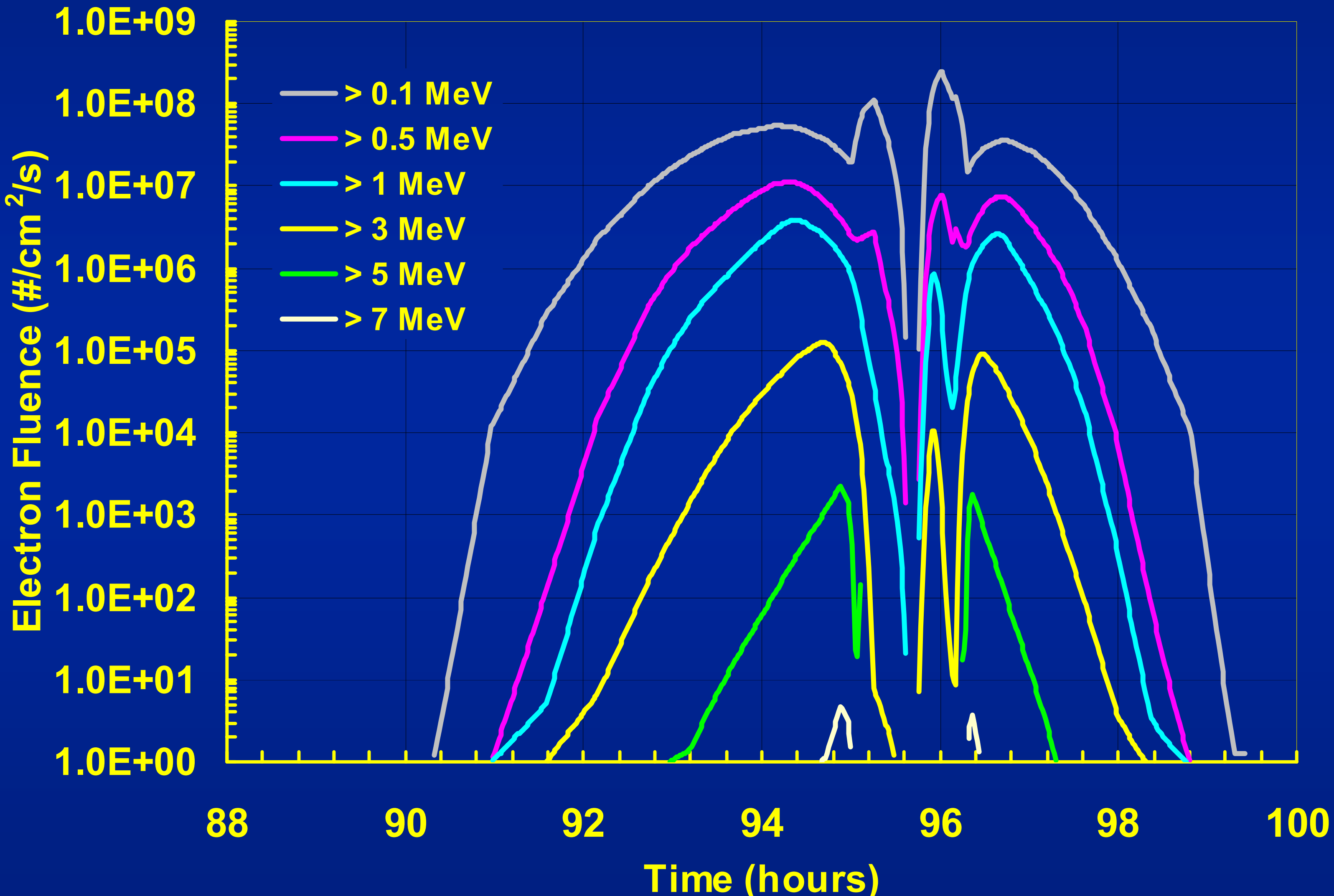


Worst Case Pass - Electrons

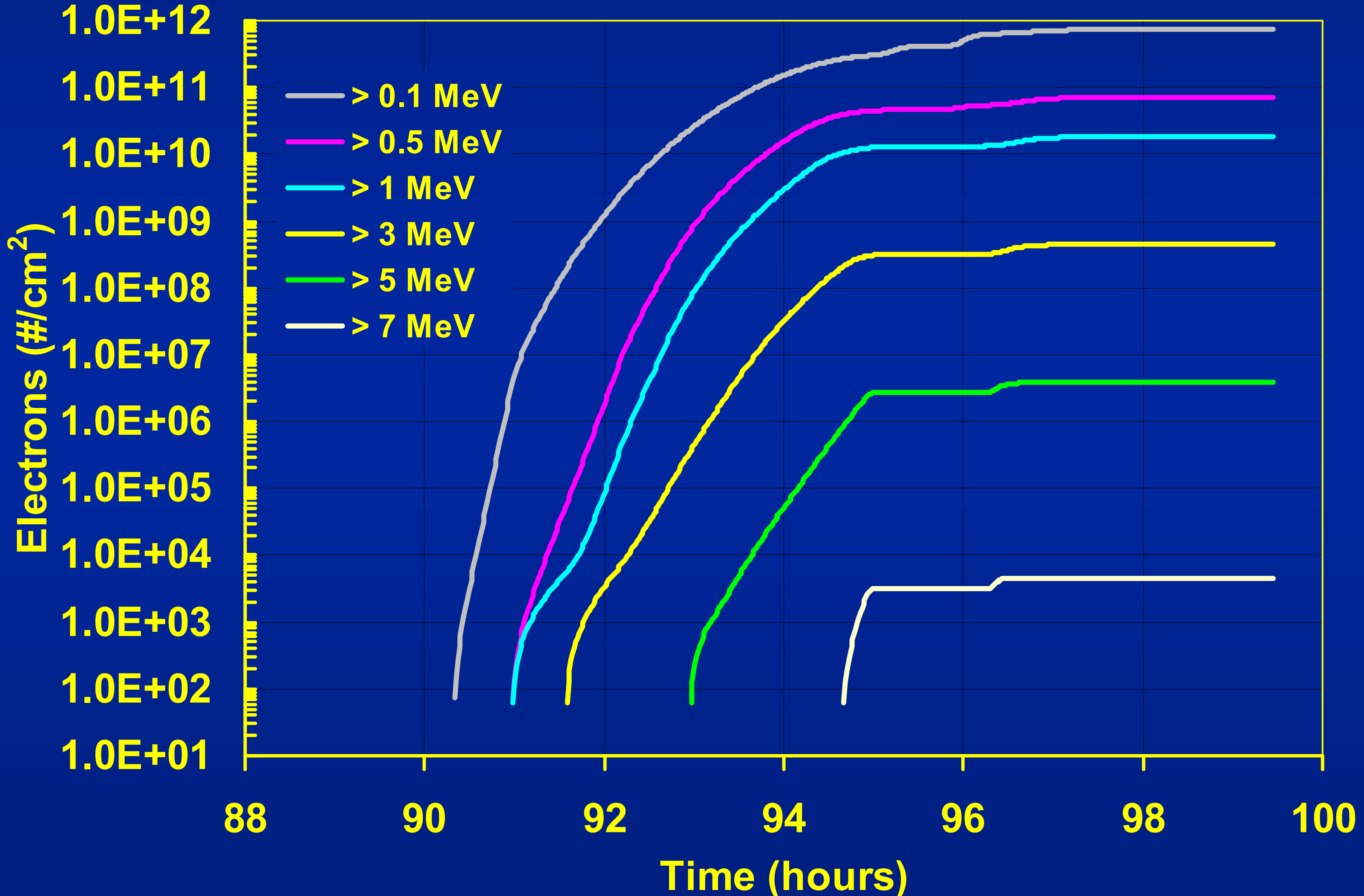
LEO/High Inclination



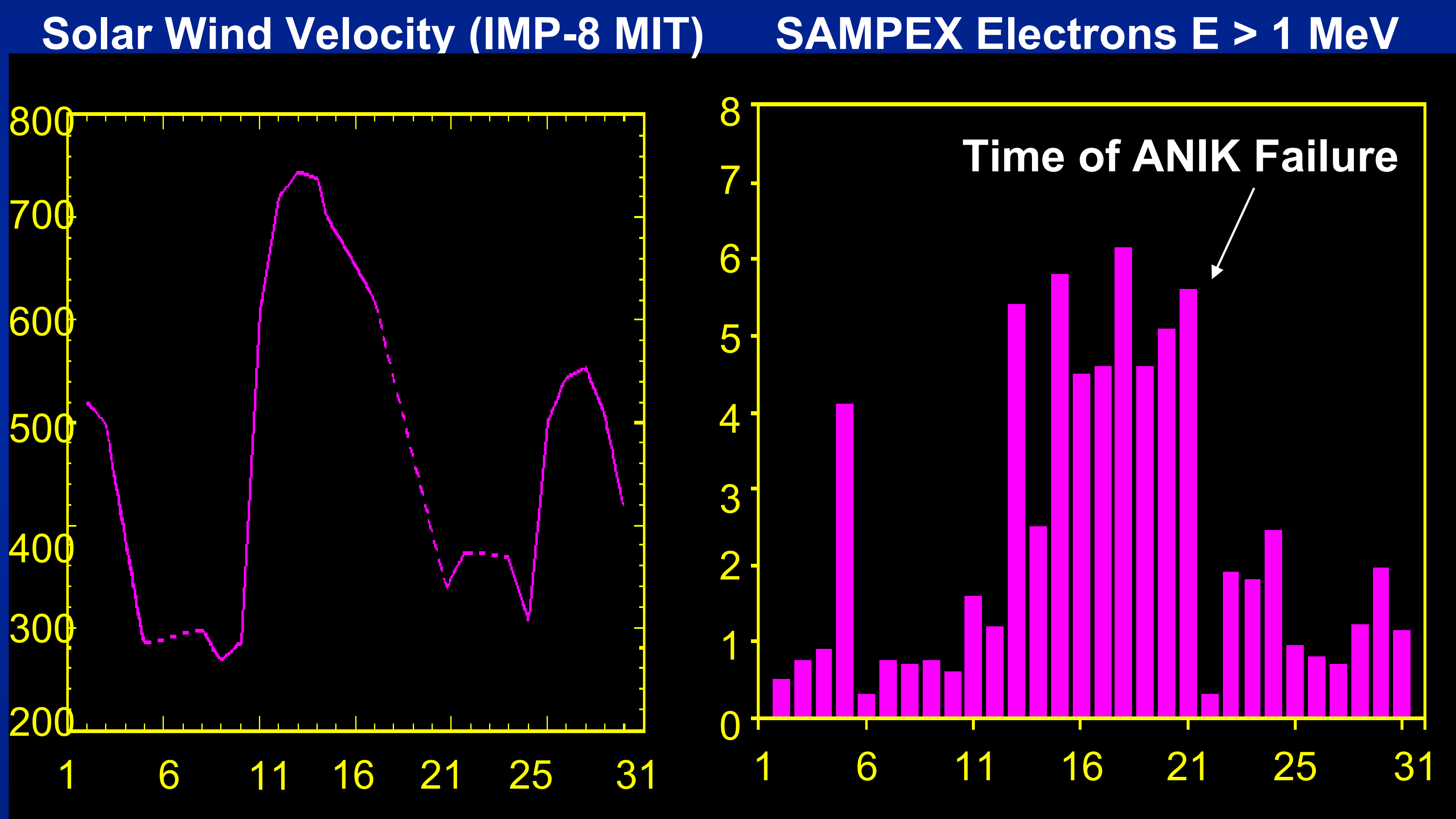
Electron Exposure - MAP



Accumulated Electrons - MAP



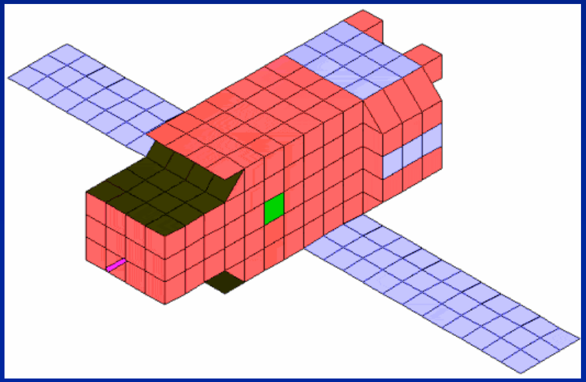
ANIK E1: Magnetic Storm



January 1994

System Hardening for Spacecraft Charging

- Two distinct problems
  - » Surface charging
  - » Deep-dielectric charging
- Risk Avoidance
  - » Assume there will be a problem
  - » Evaluate with NASCAP 2K
  - » Follow accepted design practices
    - Grounding
    - Shielding
    - Material selection
    - Circuit design



Summary of Radiation Environments

Environment Levels

Examples

Low: < 10 krads
- Short mission durations
- Moderate single event effects environment
- Low displacement damage environment

Low altitude/
low inclination
(HST, Shuttle, XTE)

Moderate: 10-100 krads
- Medium mission duration
- Intense single event environment
- Moderate displacement damage environment

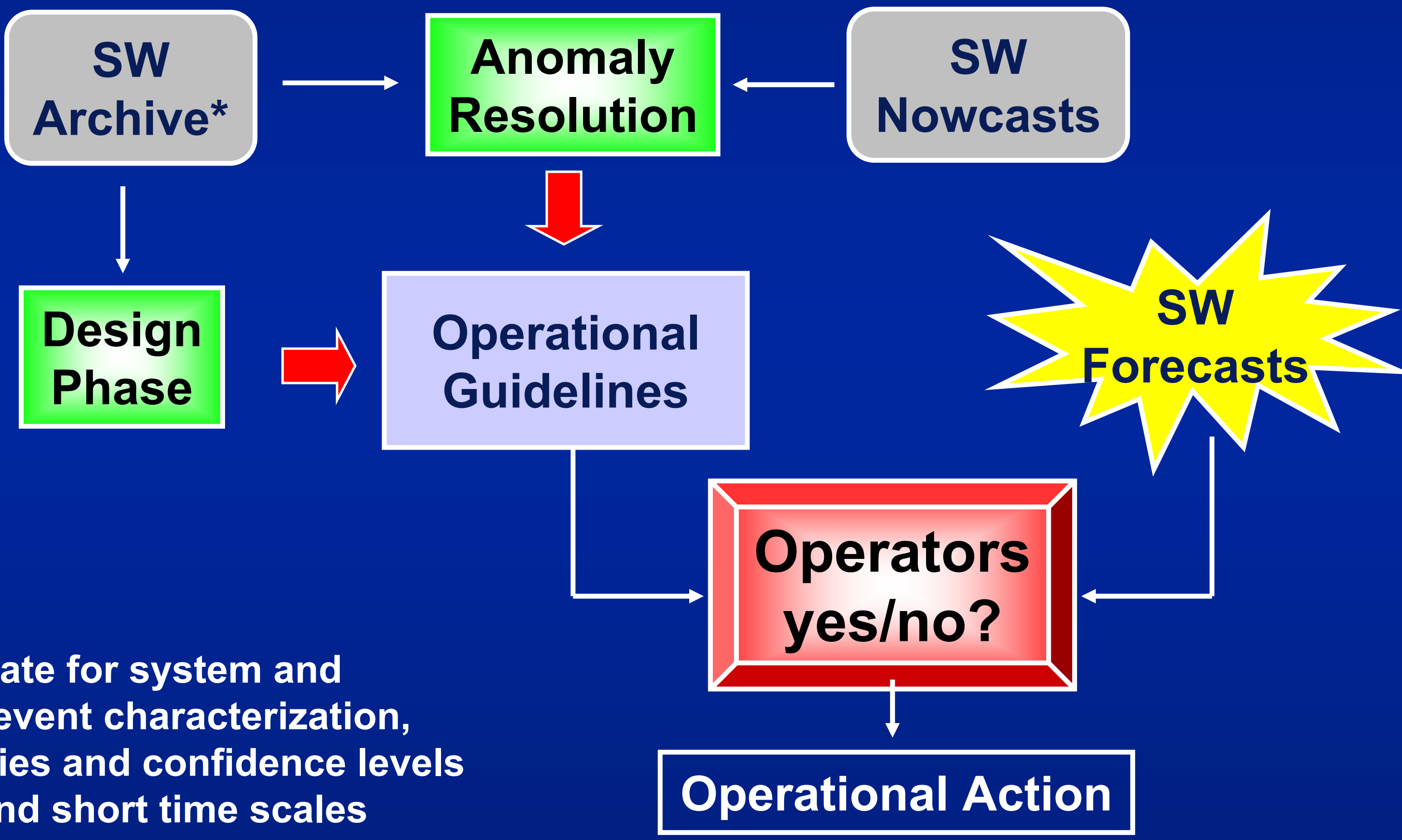
Low altitude/
high inclination
(EOS, GLAS)
L1, L2, GEO

High: >100 krads
- Long mission duration
- Intense single event effects environment
- Intense displacement damage environment

Europa, GTO,
MEO, << 1 AU

after LaBel

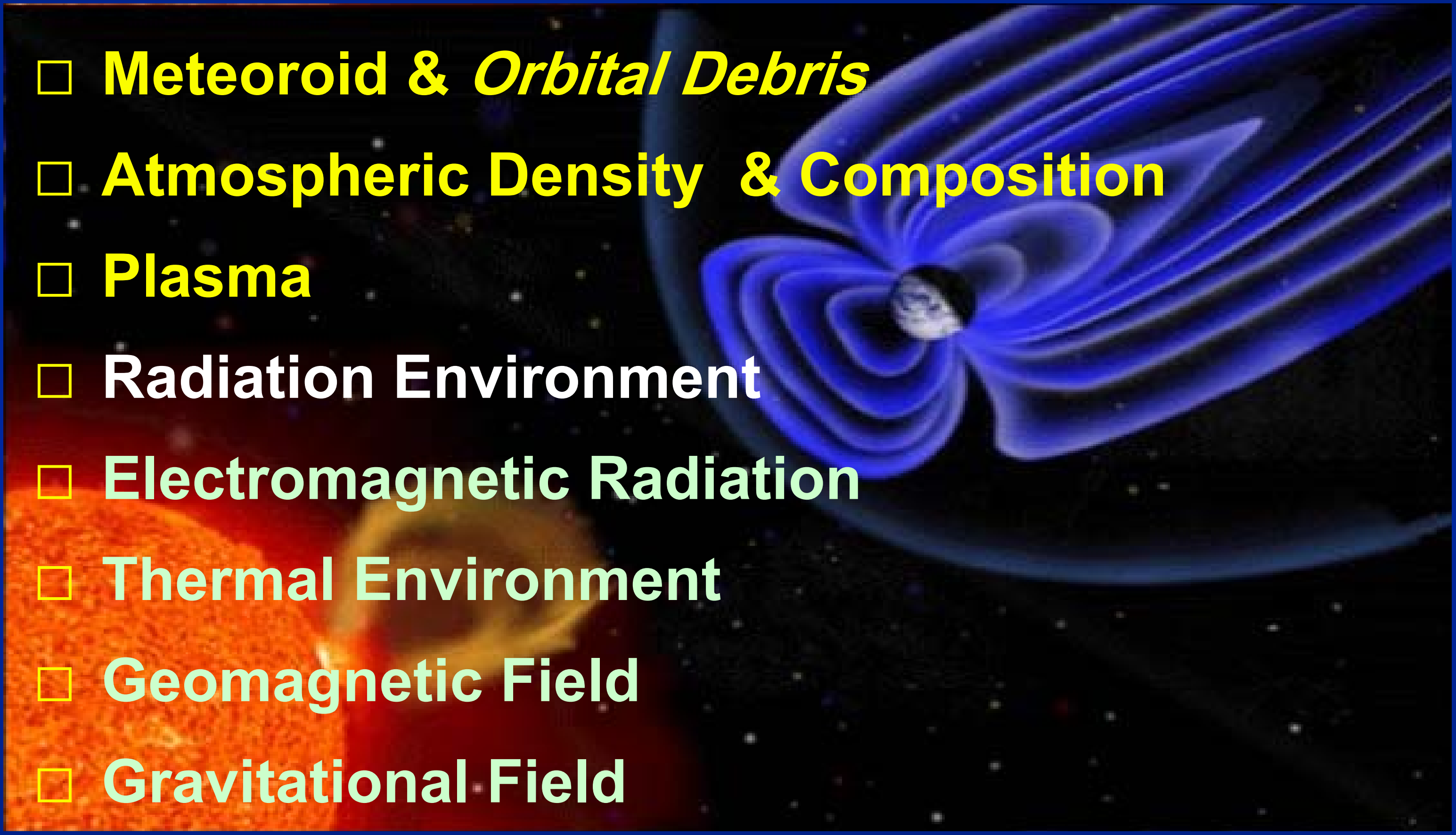
Increasing Need for Operational Guidelines Space Weather



***Appropriate for system and location, event characterization, probabilities and confidence levels on long and short time scales**

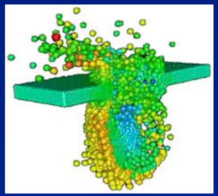
Atmospheric Environments

Natural Environments



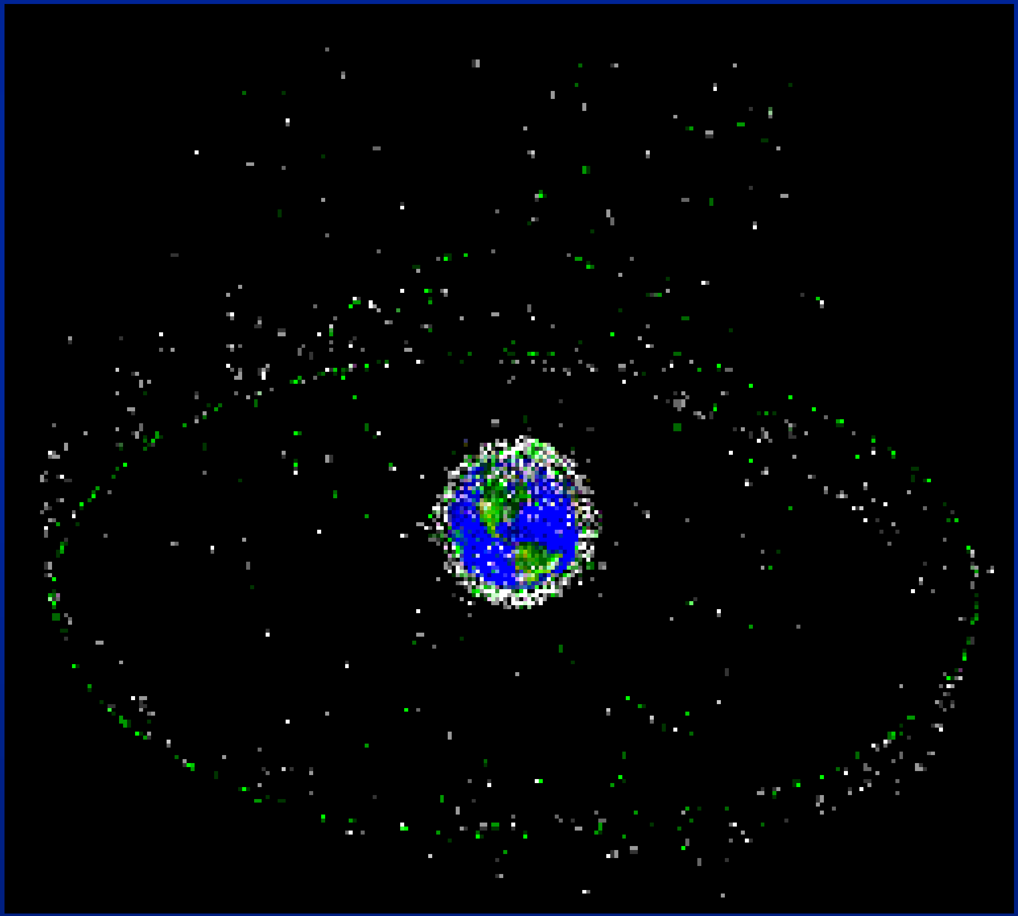
- Meteoroid & *Orbital Debris*
- Atmospheric Density & Composition
- Plasma
- Radiation Environment
- Electromagnetic Radiation
- Thermal Environment
- Geomagnetic Field
- Gravitational Field

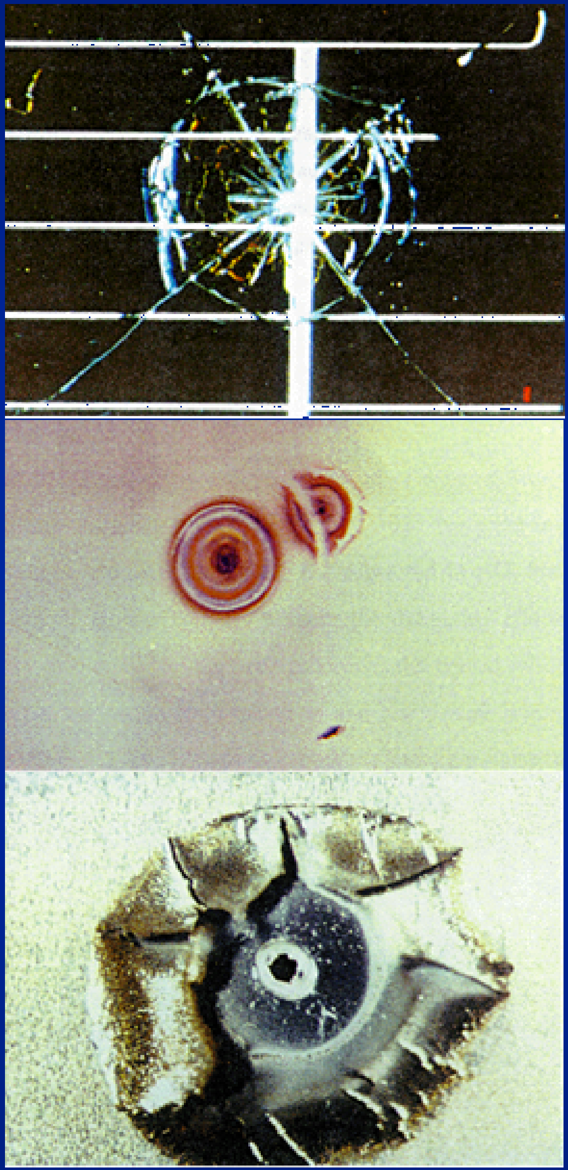
Meteoroid/Orbital Debris



- Meteoroids
  - » Primarily remnants of comet orbits
    - – Several times a year Earth intersects a comet orbit
  - » Asteroid belt
    - – Sporadic particles on a daily basis
- Debris
  - » Operational payloads, Spent rockets stages, Fragments of rockets and satellites, Other hardware and ejecta
  - » USAF Space Command tracks over 7,000 > 10 cm objects in LEO
  - » Tens of thousands smaller objects

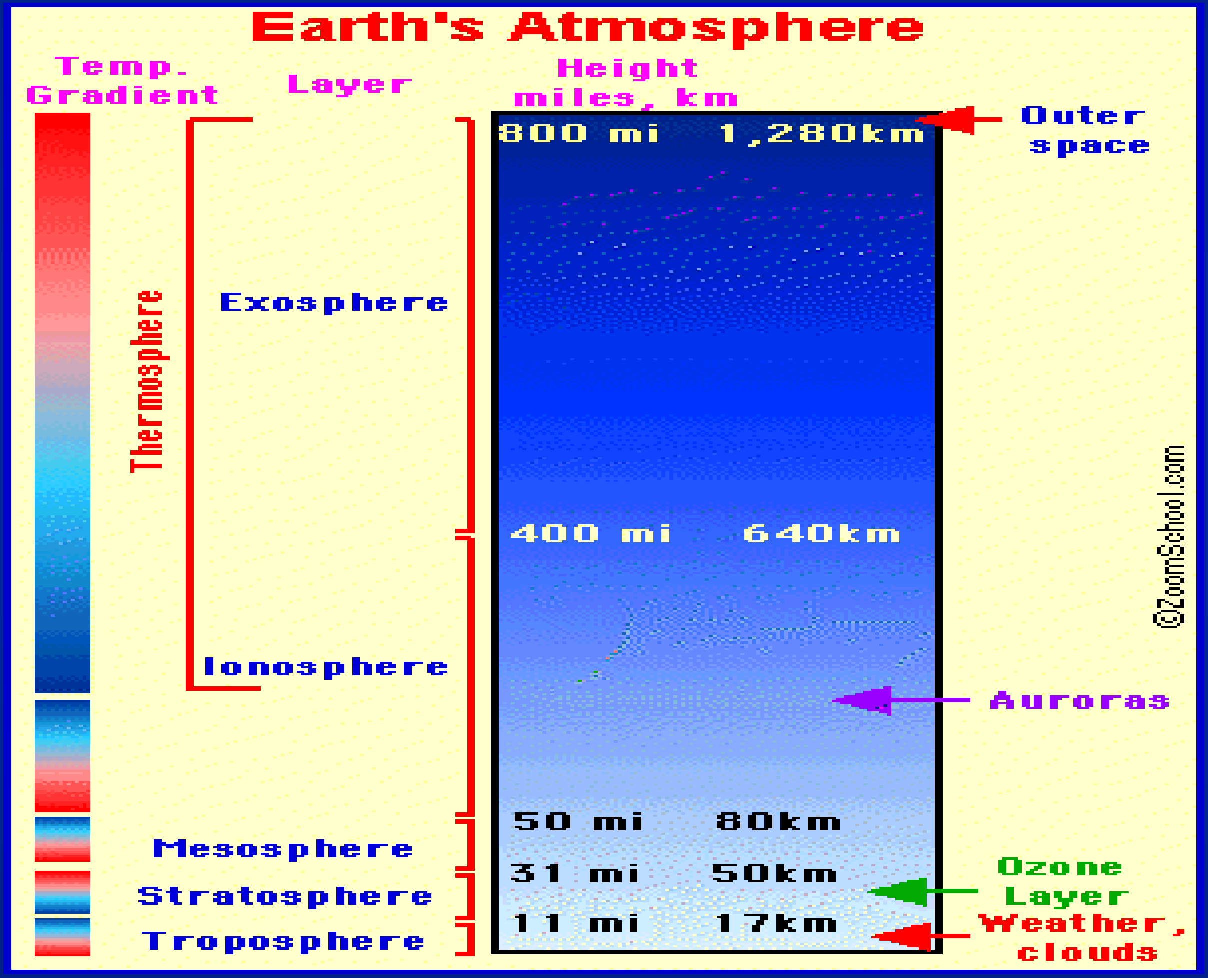
The Threat





Penetration through an aluminized Mylar foil

Atmospheric Environments



Neutral Thermosphere

- Definition
  - Atmospheric Density, Density Variations, Atmospheric Composition (AO), Winds
- Neutral atmospheric constituents
- 90 – 600 km
- Neutral gas particles
  - Lower – Atomic oxygen (AO)
  - Higher – Hydrogen & Helium
- Altitude variations due to temperature
  - Solar cycle effects due to absorption of solar extreme ultraviolet radiation (EUV)
  - Proxy measurement with 10.7-cm radio flux (F10.7)

Spacecraft Effects

- Spacecraft drag
  - Density of neutral gas
  - Altitude decay & torques
- Materials degradation - Erosion
  - Thermal, mechanical, optical properties
  - AO (200 – 400 km) - solar cycle dependent
  - Effects aggravated by micrometeoroid impacts, sputtering, UV exposure, contamination
- Spacecraft glow
  - Optical emissions generated by excitation of metastable molecules
  - Surface acts as catalyst – material dependent

Definition of Contamination

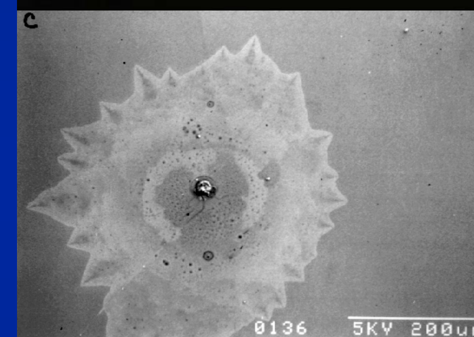
An unwanted material or substance that causes degradation in the desired function of an instrument or flight hardware

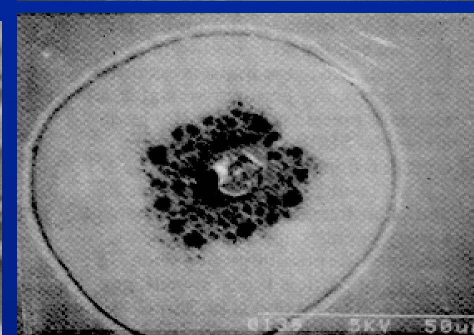
Systems Affected

- Optical components – lenses & mirrors
- Thermal control - external paints & blankets
- Guidance – baffles
- Any sensitive surfaces
  - » Exposed to all environments!

Effects

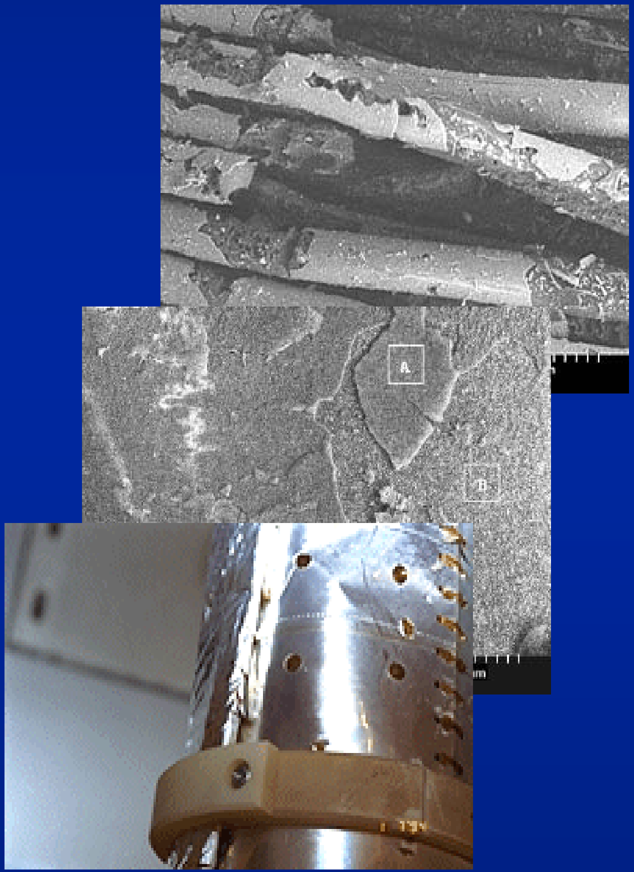
- Charging
- Glow
- False signals on optical detectors
- Surface erosion





Contamination Processes

- Particulates and gases
  - Thermal vacuum outgassing
  - Engine firings
  - Plume impingement
- Natural Environments
- Aggravating factors
  - Electromagnetic radiation
    - UV
    - Infrared
  - Thermal environment
    - High temperatures
    - Temperature cycling



Mission Phases for Contamination

- An Issue at All Mission Phases
  - » Construction & Assembly
  - » Ground Handling & Transportation
  - » Launch
  - » Orbital Insertion
  - » Early Outgassing
  - » Long Term Exposure
  - » Recovery

Contamination Risk?

Thermal control surfaces?

H < 1000 km?

Instrument calibration?

Solar UV?

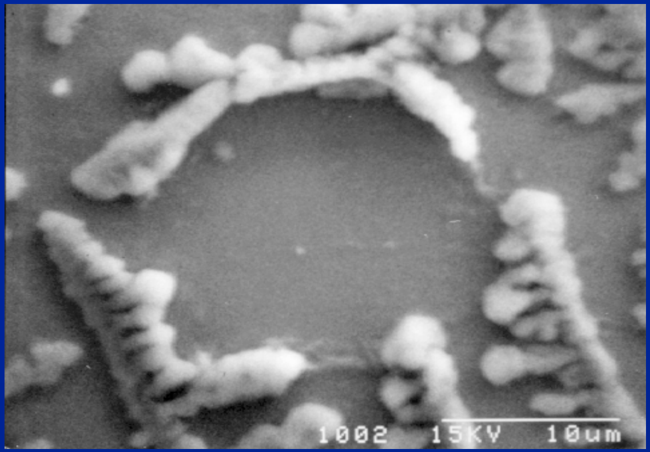
Baffle design?

Earth albedo UV?

Lens design?

UV instruments?

Detector design?



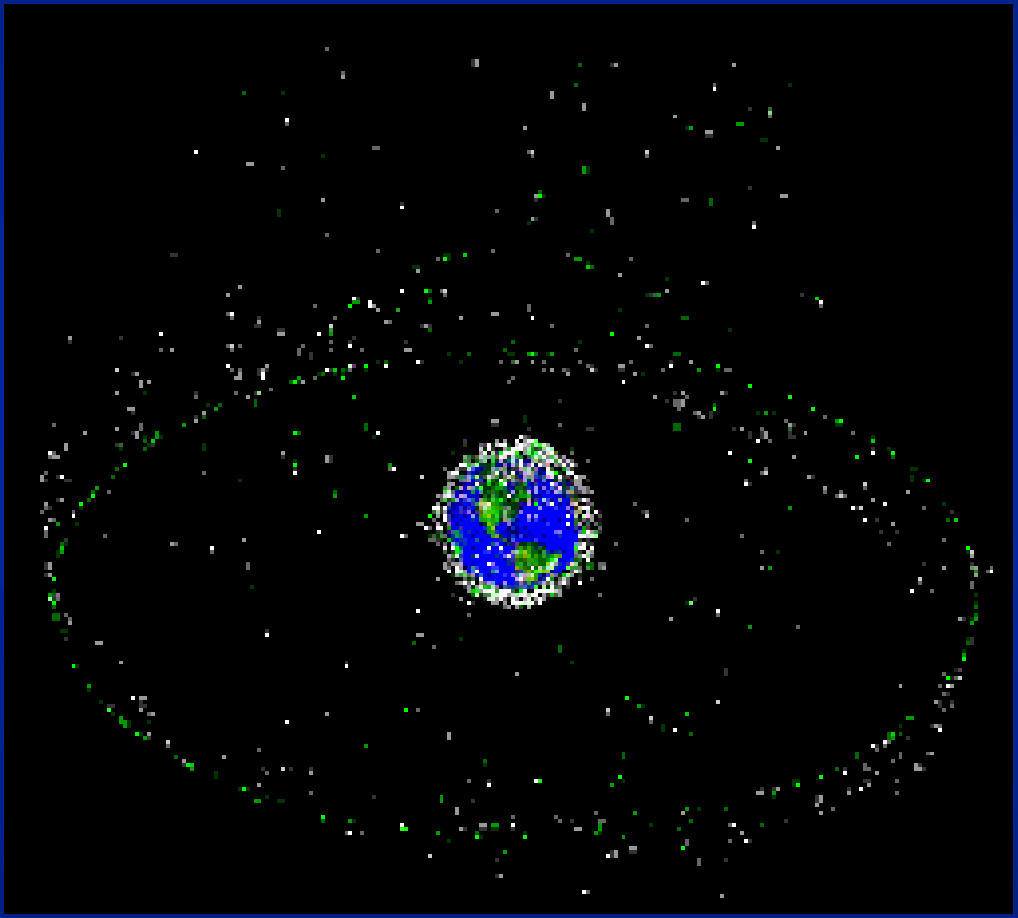
IR instruments?

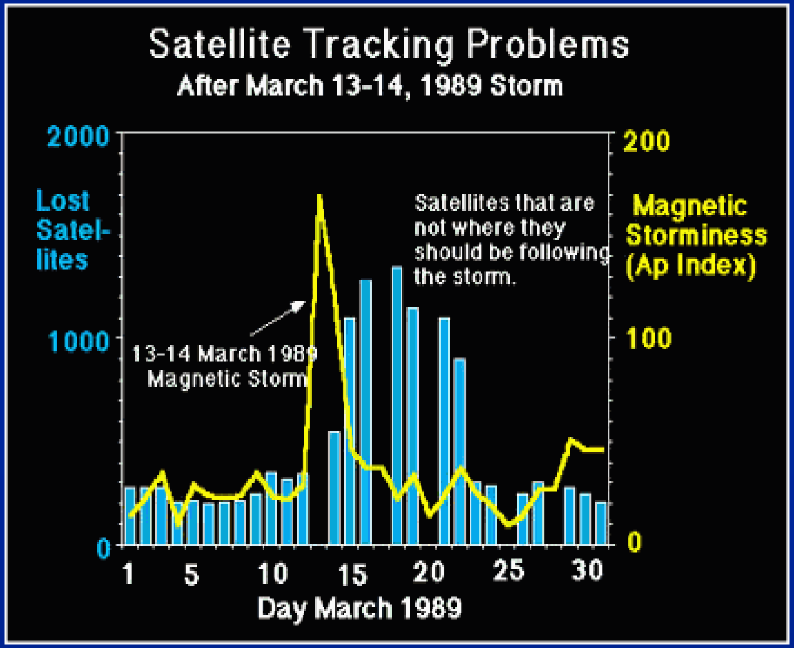
Mirror design?

Spacecraft lifetime?

Cooled detector systems?

Spacecraft Drag

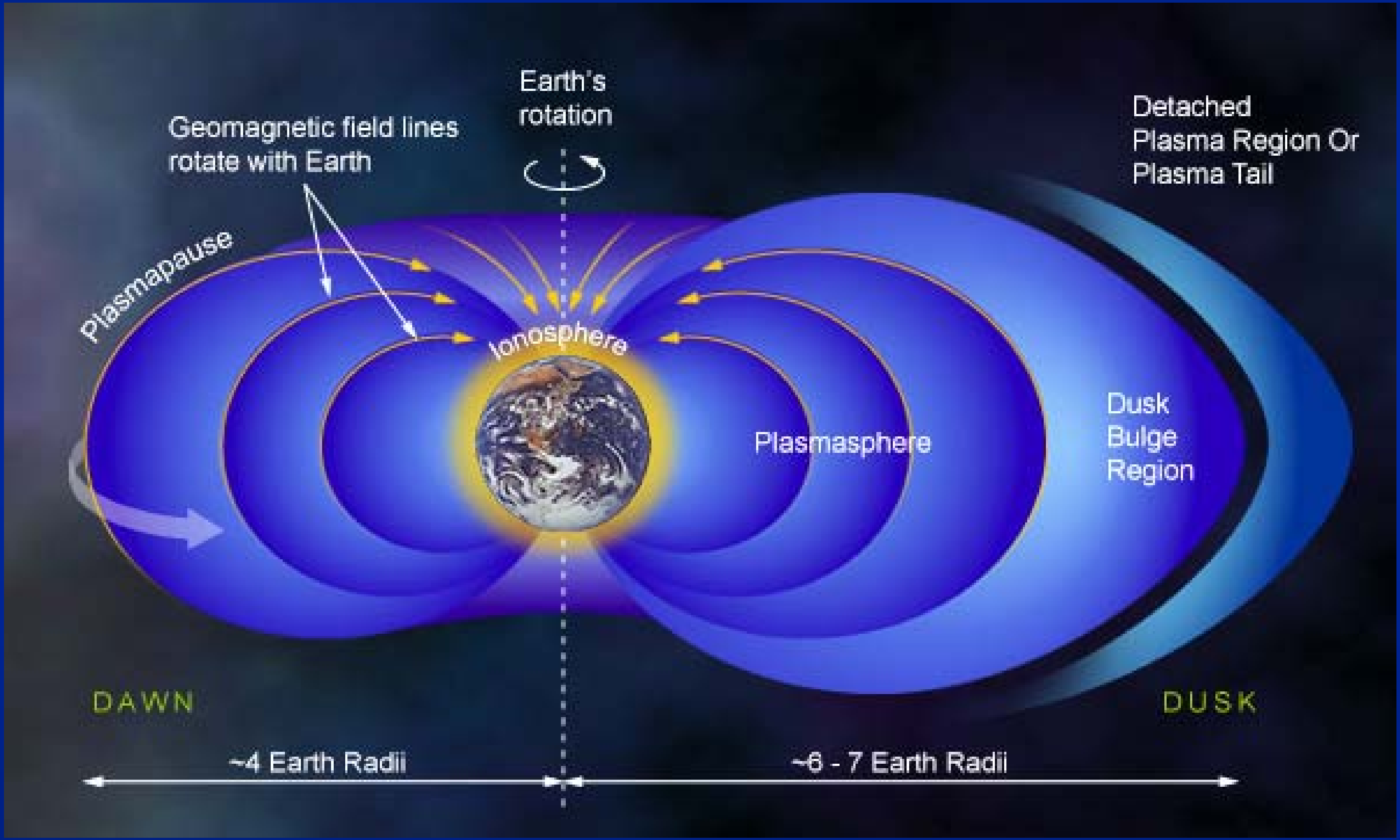




Plasma Environment

- Energy < 100 keV - No radiation effects
- Ionized gas where electron and ion densities are approximately equal
- Sources
  - Ionosphere
    - Electrically charged portion of the atmosphere
    - Low energy (eV)/High Density
  - Geomagnetic substorm activity
    - High energy (keV)/Low density
  - Solar Wind
    - Sun’s corona
    - Seen at > 10 Billion km from the Sun
- Dramatic variation with altitude, latitude, magnetic field strength, and solar activity

Plasmasphere



Plasma Interactions – Ionosphere

- Supersonic spacecraft motion through background ions in the plasma
- Solar array coupling to plasma
  - » Current drain on solar arrays
- Contamination
  - » Dense pressure of atmosphere in LEO
  - » Modification of ambient atmosphere by outgassing
- Generation and emission of plasma waves
- Polar regions – High level of charging
  - » Exposure to auroral electrons, esp. if current collection occurs in ion-depleted wake zones
  - » Increased surface contamination